Joint CTEQ Meeting and POETIC 7 (7th International Conference on Physics Opportunities at an ElecTron-Ion-Collider)

Temple University

November 14-18, 2016

QCD Theory @ EIC

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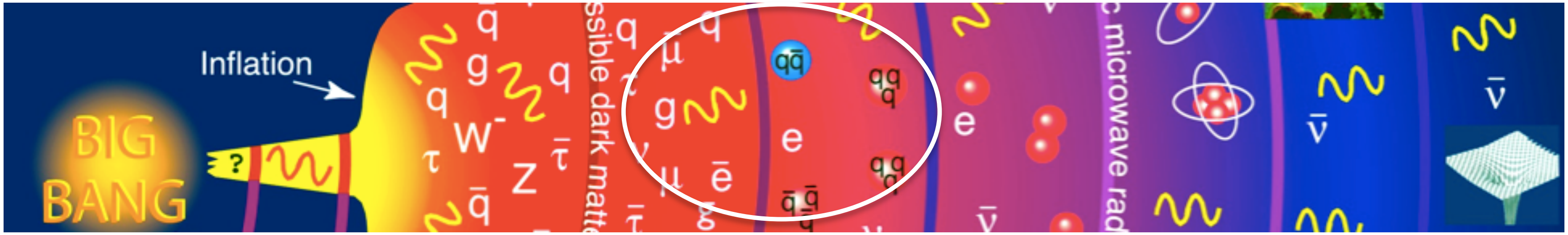
Theory Center, Jefferson Lab

Acknowledgement: Some of the physics presented here are based on the work of EIC White Paper Writing Committee put together by BNL and JLab managements, …

See also talk by Aschenauer for exp't

21st Century Nuclear Science

- What is the role of QCD in the evolution of the universe?



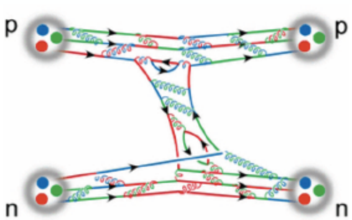
- How hadrons are emerged from quarks and gluons?
- How does QCD make up the properties of hadrons?

  Their mass, spin, magnetic moment, …

- What is the QCD landscape of nucleon and nuclei?

Color Confinement — Asymptotic freedom — Q (GeV)

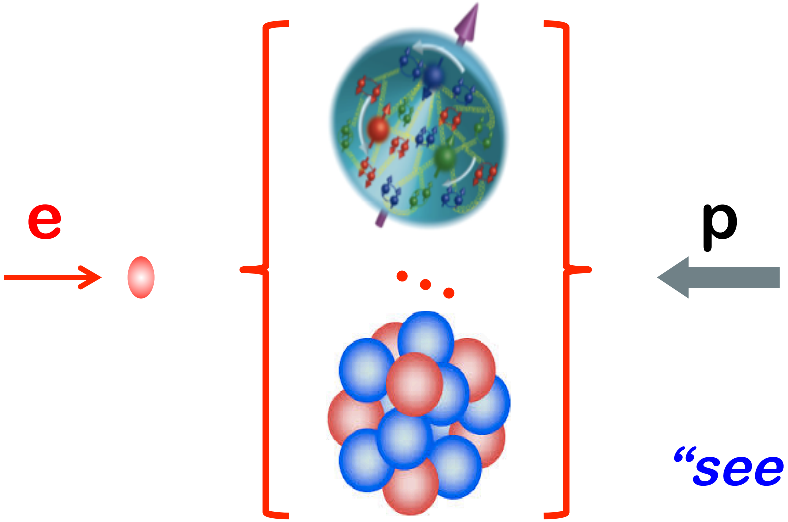
200 MeV (1 fm) — 2 GeV (1/10 fm) — Probing momentum

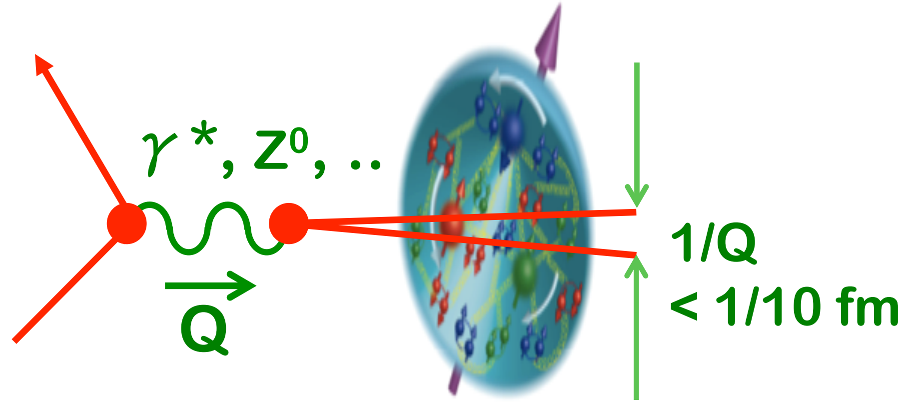


- How do the nuclear force arise from QCD?
- Extended family of hadrons? XYZ? …

Electron-Ion Collider (EIC)

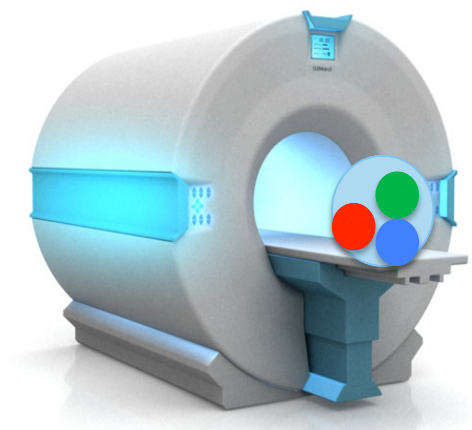
- A giant "Microscope" – "see" quarks and gluons by breaking the hadron





"see" the non-linear dynamics of the glue!

- A sharpest "CT" – "imagine" quark/gluon without breaking the hadron



  – "cat-scan" the nucleon and nuclei with better than 1/10 fm resolution

  – "see" the proton "radius" of gluon density

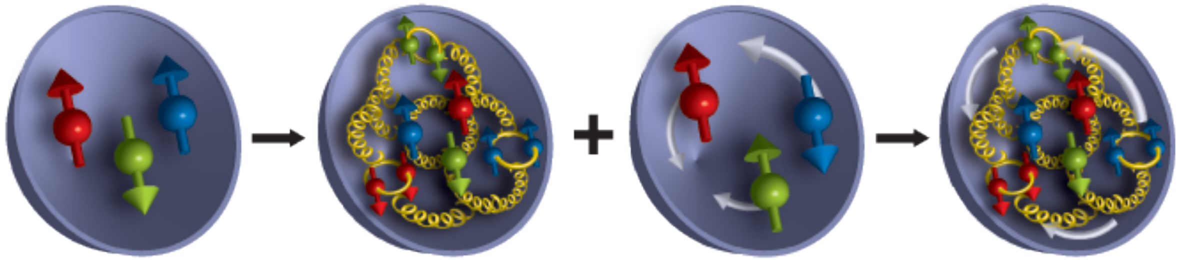
- Why now?

  Exp: advances in luminosity, energy reach, detection capability, …

  Thy: breakthrough in factorization – "see" confined quarks and gluons, …

How to "see" and quantify hadron structure?

- Our understanding of hadron evolves



1970s 1980s/2000s Now

Nucleon is a strongly interacting, relativistic bound state of quarks and gluons

- Challenge:

  No modern detector can see quarks and gluons in isolation!

- Question:

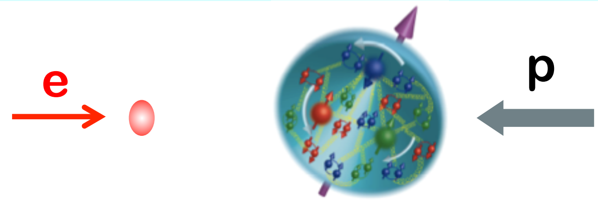
  How to quantify the hadron structure if we cannot see quarks and gluons? *We need the probe!*

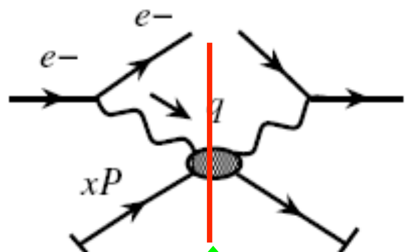
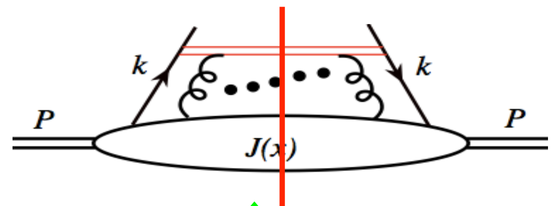
- Answer:

  QCD factorization! *Not exact, but, controllable approximation!*

QCD Factorization: connecting parton to hadron

- One hadron:



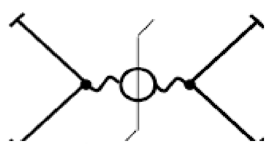
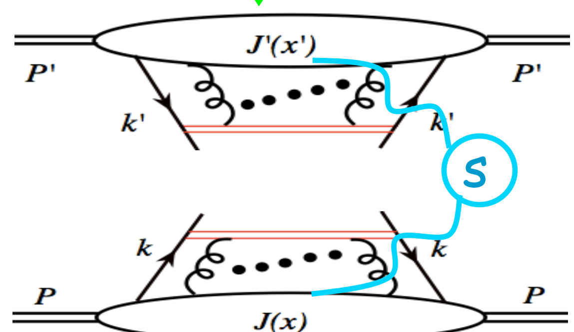
$\sigma_{\mathrm{tot}}^{\mathrm{DIS}} \sim$  $\otimes$  $+\, O\left(\frac{1}{QR}\right)$

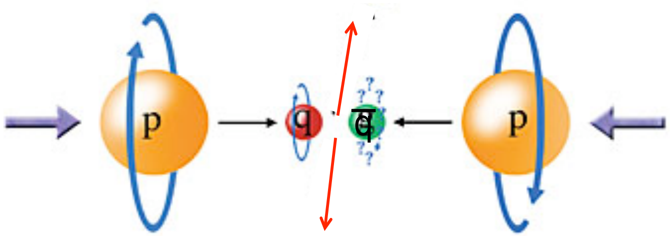
Hard-part
Probe

Parton-distribution
Structure

Power corrections
Approximation

- Two hadrons:

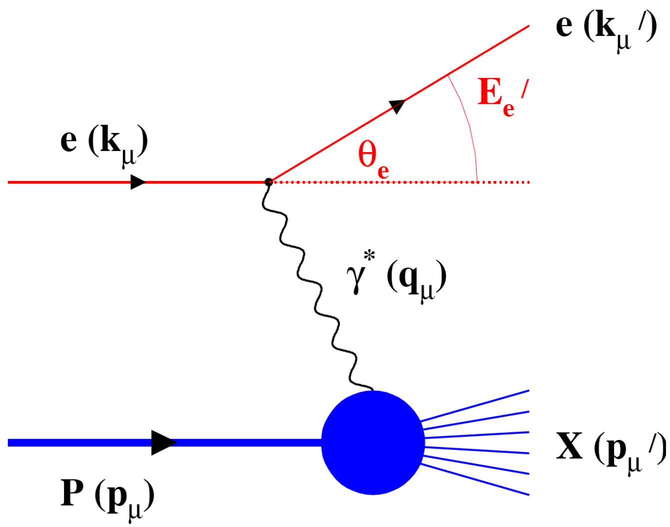
$\sigma_{\mathrm{tot}}^{\mathrm{DY}} \sim$  $\otimes$  $+\, O\left(\frac{1}{QR}\right)$



Predictive power:
Universal Parton Distributions

Many complementary probes at one facility

- Lepton-hadron facility – many factorizable observables:



Q^2 → Measure of resolution

y → Measure of inelasticity

x → Measure of momentum fraction of the struck quark in a proton

$$Q^2 = S\, x\, y$$

Inclusive events: e+p/A → e'+X

Detect only the scattered lepton in the detector

Semi-Inclusive events: e+p/A → e'+h(π,K,p,jet)+X

Detect the scattered lepton in coincidence with identified hadrons/jets

Exclusive events: e+p/A → e'+ p'/A'+ h(π,K,p,jet)

Detect every things including scattered proton/nucleus (or its fragments)

"Big" questions to be answered, …

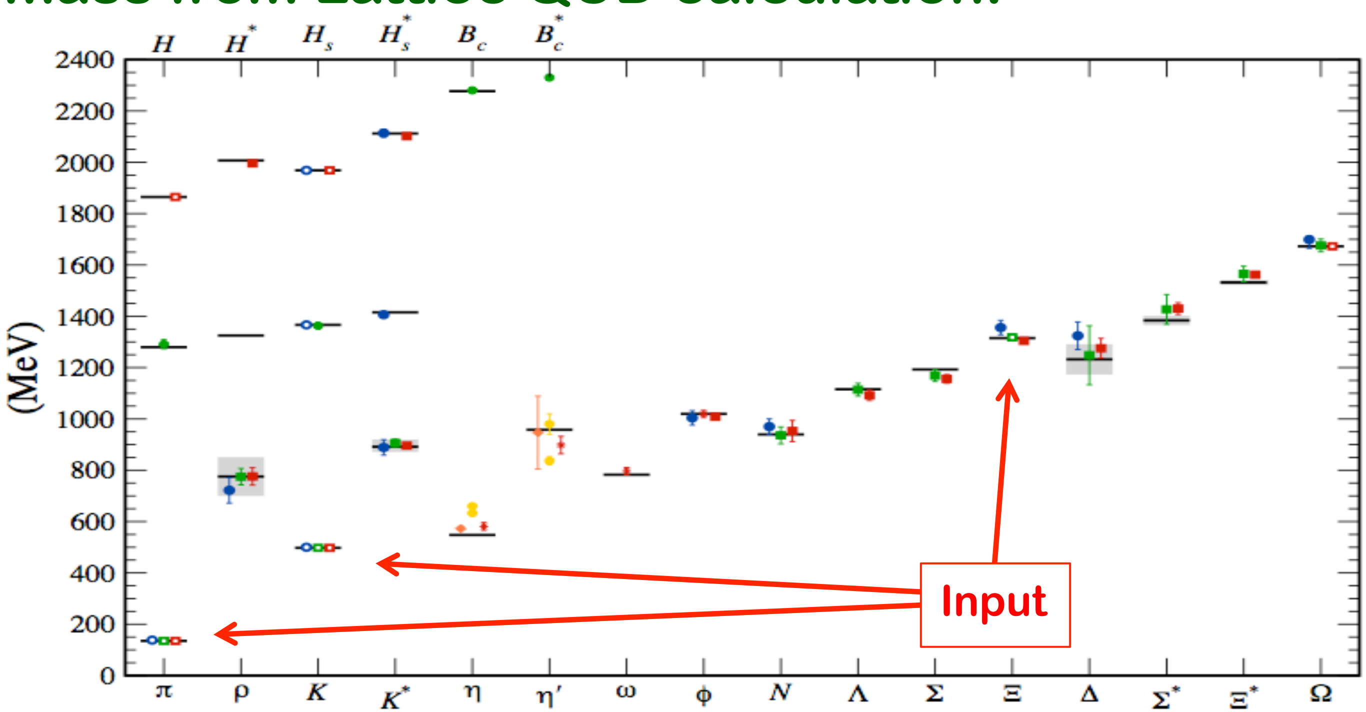
Also see Savage's talk

- ❑ How does QCD generate the nucleon **mass**?

  "… The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …"

  REACHING FOR THE HORIZON
  The 2015 Long Range Plan for Nuclear Science

- ❑ Hadron mass from Lattice QCD calculation:



"Big" questions to be answered, …

- **How does QCD generate the nucleon mass?**

"… The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …"

REACHING FOR THE HORIZON
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- **Role of quarks and gluons?**

  - QCD energy-momentum tensor:

$$T^{\mu\nu} = \frac{1}{2}\,\overline{\psi} i \overleftrightarrow{D}^{(\mu}\gamma^{\nu)}\psi + \frac{1}{4}\, g^{\mu\nu} F^2 - F^{\mu\alpha} F^{\nu}{}_{\alpha}$$

  - Trace of the QCD energy-momentum tensor:

$$T^{\alpha}_{\ \alpha} = \underbrace{\frac{\beta(g)}{2g} F^{\mu\nu,a} F^{a}_{\mu\nu}}_{\text{QCD trace anomaly}} + \sum_{q=u,d,s} m_q (1+\gamma_m)\overline{\psi}_q \psi_q$$

QCD trace anomaly $\beta(g) = -(11 - 2n_f/3)\, g^3/(4\pi)^2 + \ldots$

  - Mass, trace anomaly, chiral symmetry break, and …

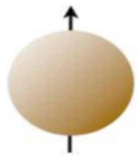
$$m^2 \propto \langle p | T^{\alpha}{}_{\alpha} | p \rangle \quad \Rightarrow \quad \frac{\beta(g)}{2g} \langle p | F^2 | p \rangle$$

⇒ quarkonium production near the threshold, from JLab12 to EIC

"Big" questions to be answered, …

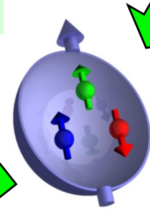
- How does QCD generate the nucleon's spin?

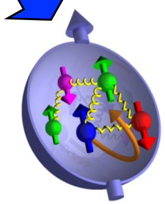
see talks by Nocera and Liu



Proton Spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_g) = \sum \langle P, S|\hat{J}^z_f(\mu)|P, S\rangle$$





Quark helicity
Best known

$$\frac{1}{2}\int dx \left(\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}\right)$$
$$\sim 30\%$$

Spin "puzzle"

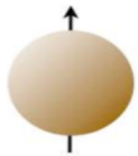
Gluon helicity
Start to know

$$\Delta G = \int dx \Delta g(x)$$
$$\sim 20\% (\text{with RHIC data})$$

Orbital Angular Momentum of quarks and gluons
Little known

“Big” questions to be answered, …

- How does QCD generate the nucleon’s spin?



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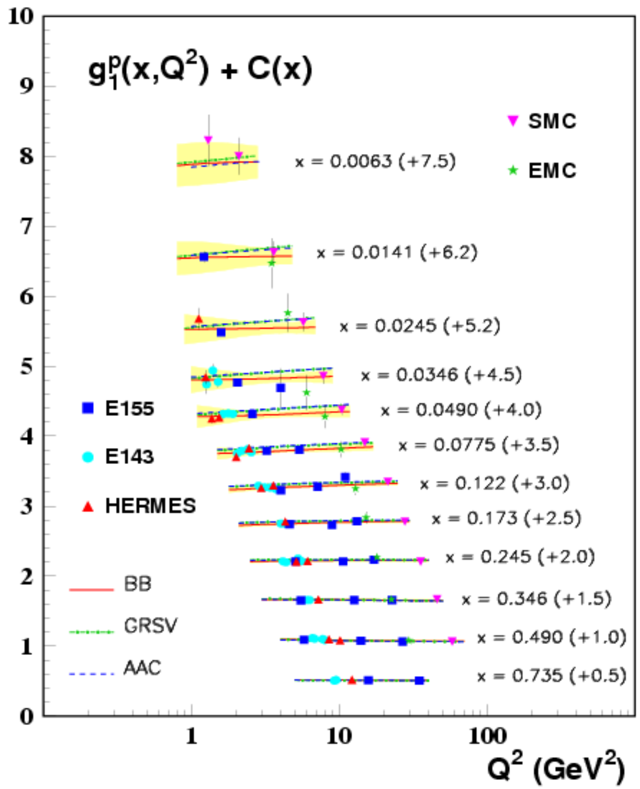
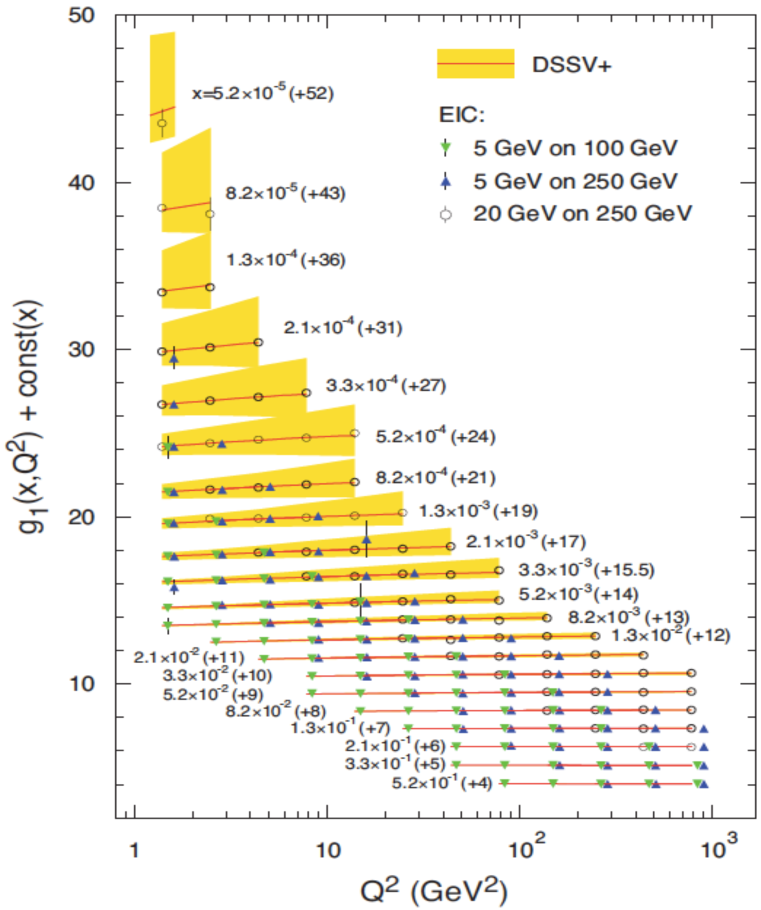
Proton Spin

- What can EIC do?



at EIC



“Big” questions to be answered, …

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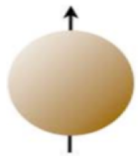
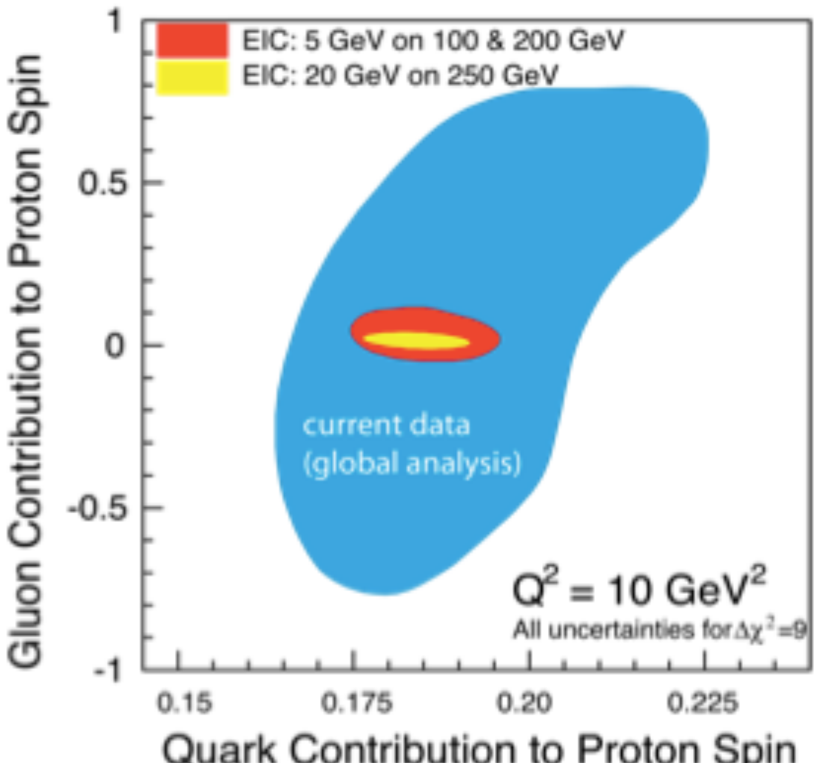


$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_g) = \sum_f \langle P, S|\hat{J}^z_f(\mu)|P, S\rangle$$

Proton Spin

- What can EIC do?



To understand the proton spin, fully, we need to understand the confined motion of quarks and gluons in QCD

→ TMDs, GTMDs, …

Need “probes” for two-scale observables!

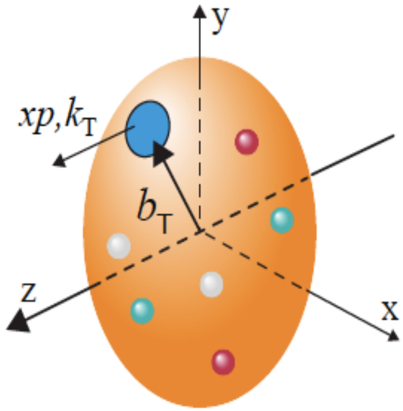
Also see talks by Mueller and Yoshida

"Big" questions to be answered, ...

❑ How to probe the confined motion of quarks and gluons?

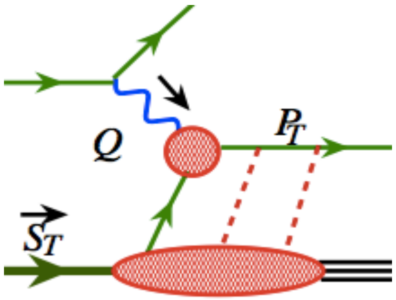
Need observables with two different momentum scales:

$$Q_1 \gg Q_2 \sim 1/R \sim \Lambda_{\rm QCD}$$

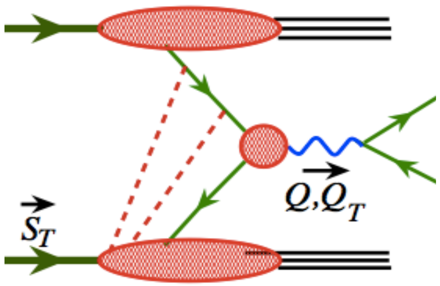


- ✧ Hard scale: Q_1 localizes the probe to see the particle nature of quarks/gluons
- ✧ "Soft" scale: Q_2 could be more sensitive to the scale of confined motion

❑ Two-scale observables with the hadron broken:



\+



\+ Two-jet momentum imbalance in SIDIS, ...

SIDIS: Q>>P_T

DY: Q>>P_T

- ✧ Natural observables with TWO very different scales
- ✧ TMD factorization: partons' confined motion is encoded into TMDs

"Big" questions to be answered, …

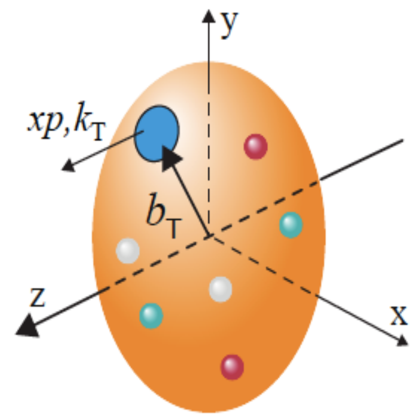
- **How to probe the confined motion of quarks and gluons?**

  Need observables with two different momentum scales:

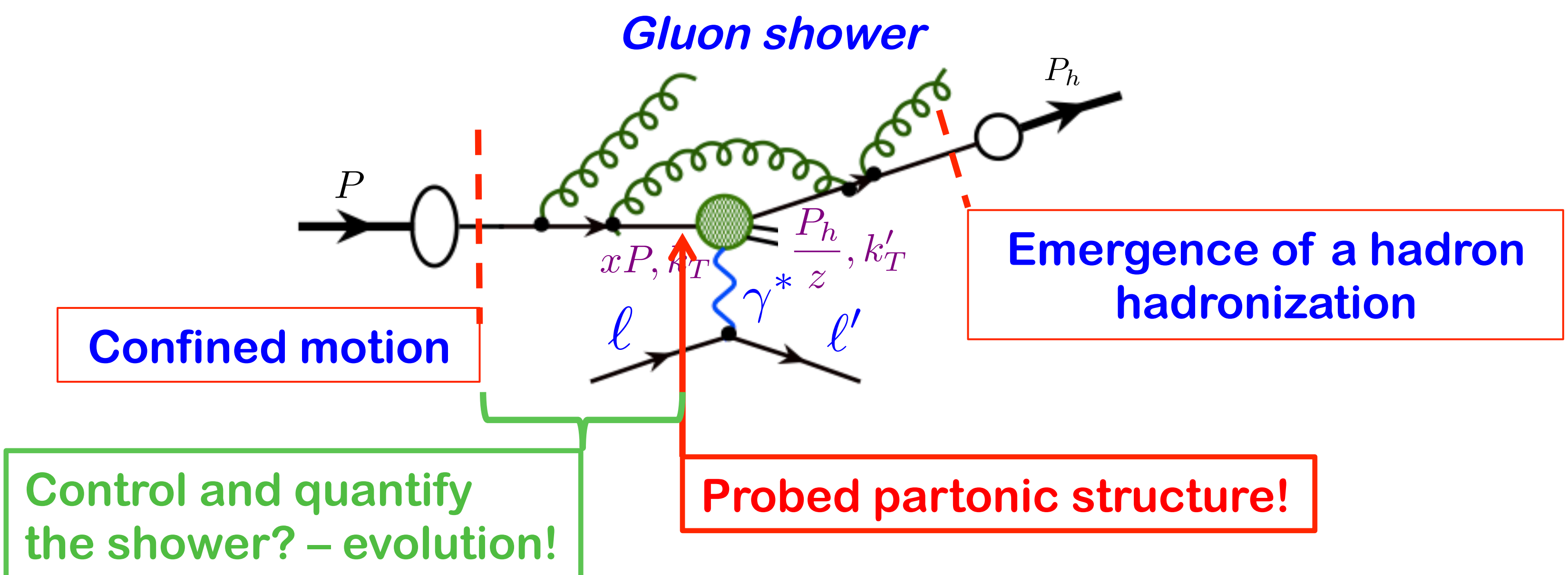
  $$Q_1 \gg Q_2 \sim 1/R \sim \Lambda_{\text{QCD}}$$

  ✧ Hard scale: Q_1 localizes the probe to see the particle nature of quarks/gluons

  ✧ "Soft" scale: Q_2 could be more sensitive to the scale of confined motion



- **"Probed" partonic structure:**



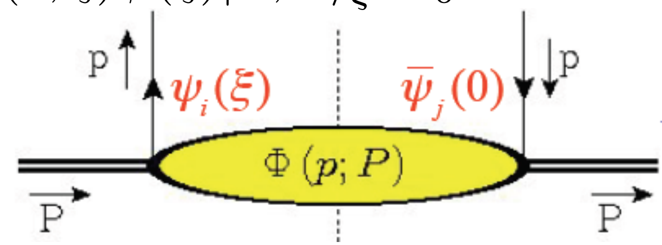
"Big" questions to be answered, ...

See also Kang's talk

❑ Definition of TMDs:

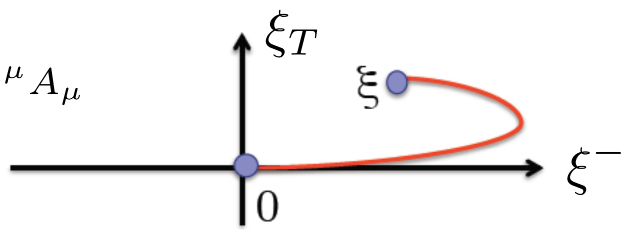
✧ In terms of matrix elements of parton correlators:

$$\Phi^{[U]}(x, p_T; n) = \int \frac{d\xi^- d^2\xi_T}{(2\pi)^3}\, e^{i\,p\cdot\xi}\, \langle P, S|\overline{\psi}(0)U(0,\xi)\psi(\xi)|P, S\rangle_{\xi^+=0}$$



✧ Depends on the choice of the gauge link:

$$U(0,\xi) = e^{-ig\int_0^\xi ds^\mu A_\mu}$$



✧ Decomposes into a list of TMDs:

$$\boxed{\begin{aligned}\Phi^{[U]}(x, p_T; n) = \Big\{ & f_1^{[U]}(x, p_T^2) - f_{1T}^{\perp[U]}(x, p_T^2)\,\frac{\epsilon_T^{p_T S_T}}{M} + g_{1s}^{[U]}(x, p_T)\gamma_5 \\ & + h_{1T}^{[U]}(x, p_T^2)\,\gamma_5\,\not{S}_T + h_{1s}^{\perp[U]}(x, p_T)\,\frac{\gamma_5\,\not{p}_T}{M} + ih_1^{\perp[U]}(x, p_T^2)\,\frac{\not{p}_T}{M}\Big\}\frac{\not{P}}{2},\end{aligned}}$$

✧ IF we knew proton wave function, this definition gives "unique" TMDs!

But, we do NOT know proton wave function (may calculate it using BSE?)

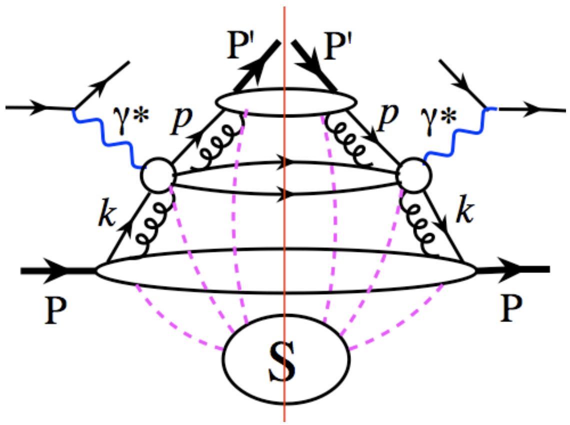
TMDs defined in this way are NOT direct physical observables!

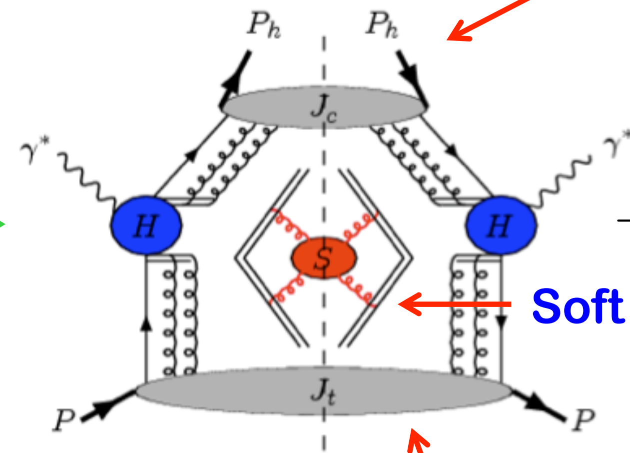
"Big" questions to be answered, ...

❑ Perturbative definition – in terms of TMD factorization:

SIDIS as an example:

TMD fragmentation





$$+\,\mathcal{O}\left(\frac{\langle k^2\rangle}{Q^2},\frac{\langle p^2\rangle}{Q^2}\right)$$

Soft factors

TMD parton distribution

❑ Extraction of TMDs:

$$\sigma_{\rm SIDIS}(Q,P_{h\perp},x_B,z_h)=\hat{H}(Q)\otimes\Phi_f(x,k_\perp)\otimes\mathcal{D}_{f\to h}(z,p_\perp)\otimes\mathcal{S}(k_{s\perp})+\mathcal{O}\left[\frac{P_{h\perp}}{Q}\right]$$

TMDs are extracted by fitting DATA using the factorization formula

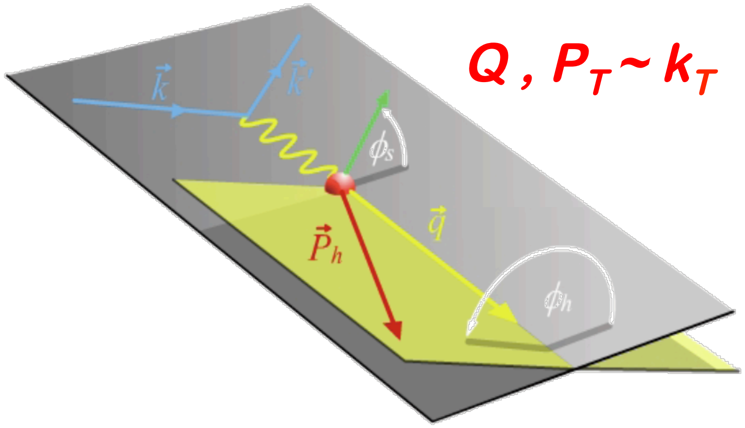
(approximation) and the perturbatively calculated $\hat{H}(Q;\mu)$.

Extracted TMDs are valid only when the <p^2> << Q^2

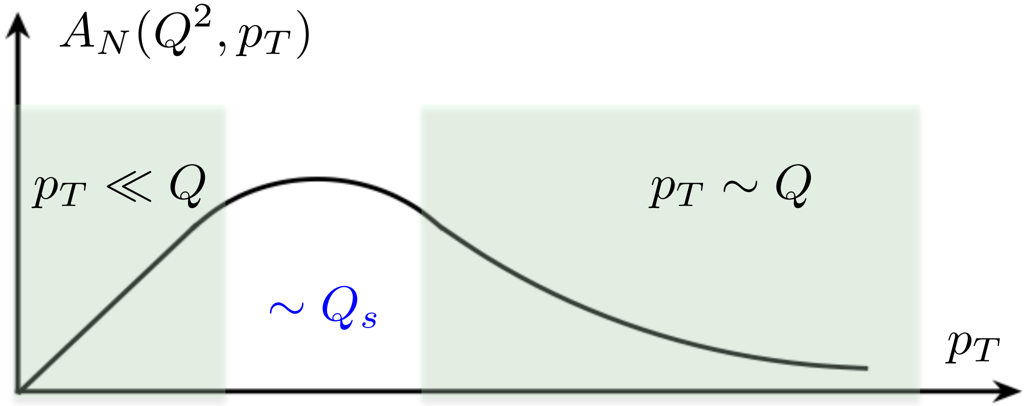
Confined motion iff the evolution is controllable!

SIDIS @ EIC

❑ Naturally, two planes, good control of the physics to probe, …



Semi-inclusive DIS



TMD Collinear Factorization

❑ Single transverse-spin asymmetry:

$$A_{UT}(\varphi_h^l, \varphi_S^l) = \frac{1}{P} \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

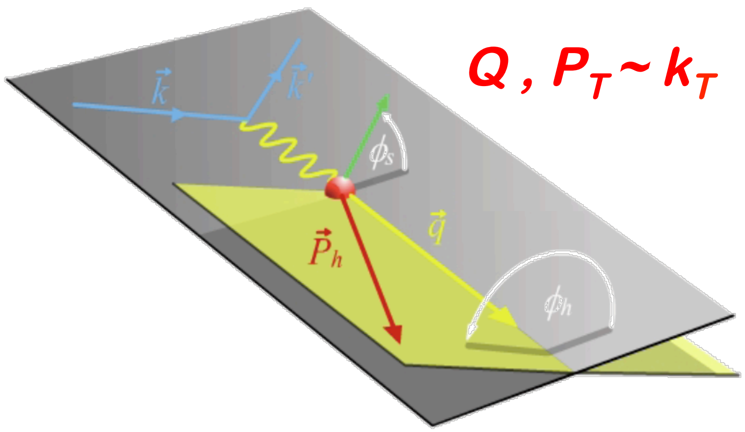
$$= A_{UT}^{Collins} \sin(\phi_h + \phi_S) + A_{UT}^{Sivers} \sin(\phi_h - \phi_S)$$

$$+ A_{UT}^{Pretzelosity} \sin(3\phi_h - \phi_S)$$

Separation of TMDs!

SIDIS @ EIC

❑ **Naturally, two planes, good control of the physics to probe, …**



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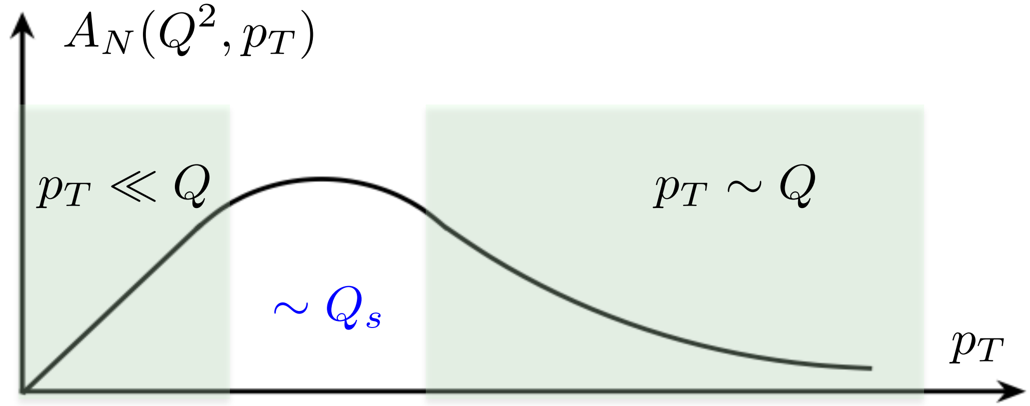

TMD

Collinear Factorization

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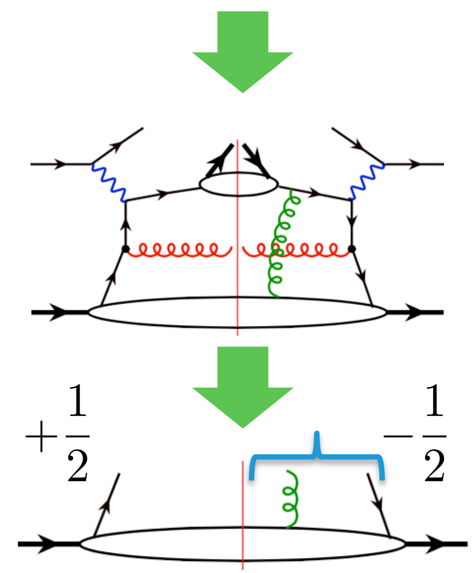
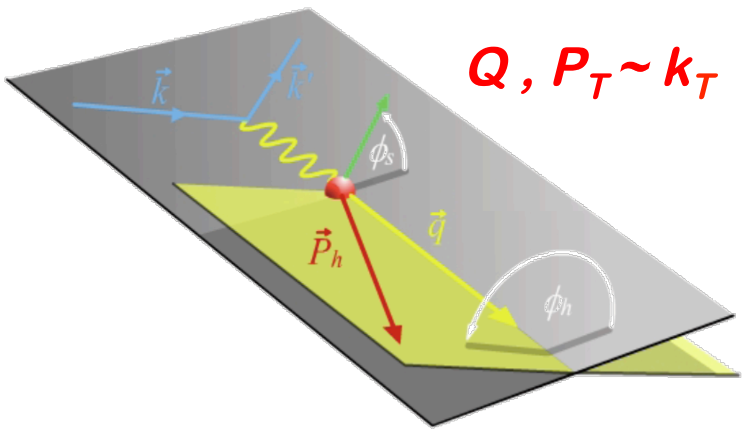
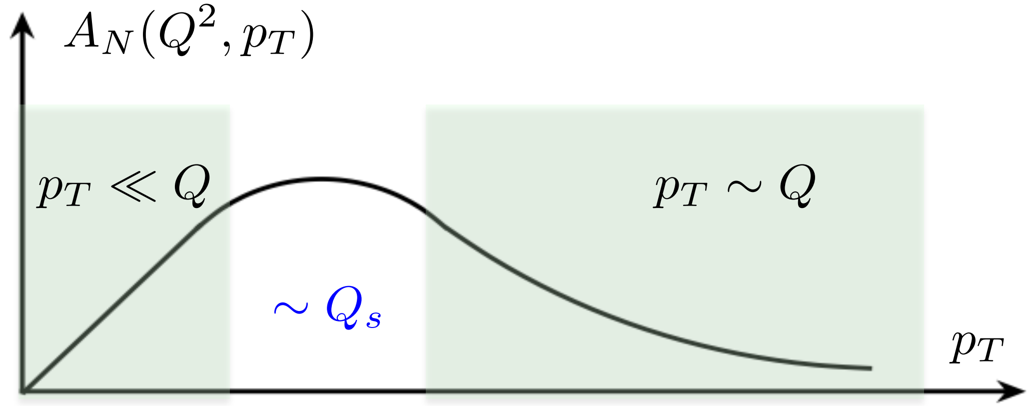


QCD quantum interference!

SIDIS @ EIC

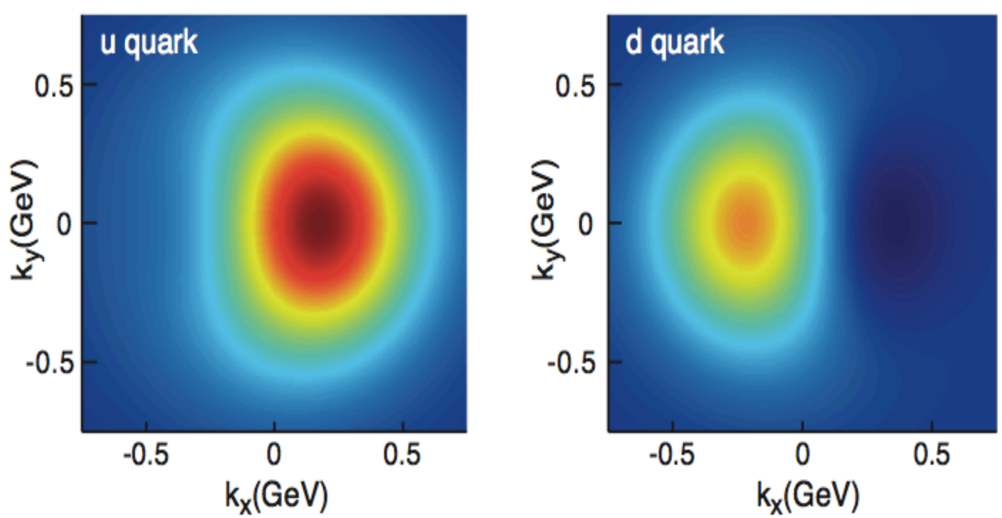
- Naturally, two planes, good control of the physics to probe, …





Semi-inclusive DIS | TMD | Collinear Factorization

- Sivers function:



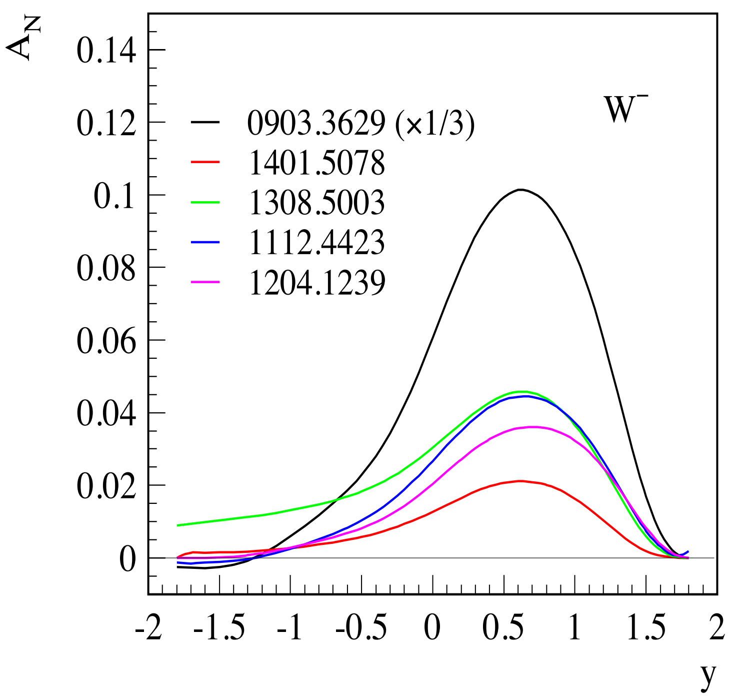
Density distribution of an unpolarized
quark in a proton moving in z direction
and polarized in y-direction

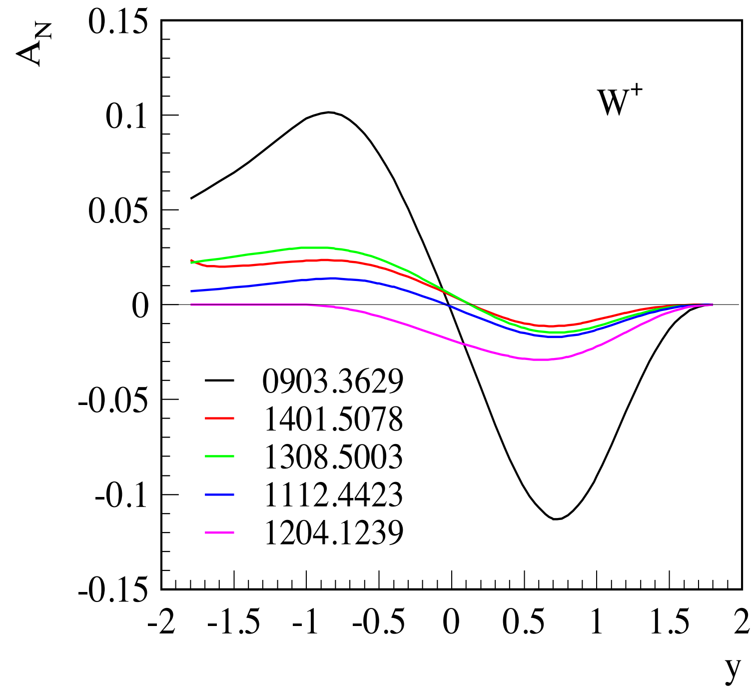
Correlation between hadronic property and partonic dynamics

"Predictions" for A_N of W-production at RHIC?

See also Kang's talk

- Scale dependence of TMDs - evolution:





- Role of non-perturbative input:

Collins & Rogers 2016

…

$$\mathcal{F}^{\rm NP} \approx b^2 (a_1 + a_2 \ln(Q/Q_0) + a_3 \ln(x_A x_B) + \ldots) + \ldots$$

At Q ~ 1 GeV, $\ln(Q/Q_0)$ term may not be the dominant one! $(Q_0/Q)^n$-term?

TMD collaboration proposal: Lattice, theory & Phenomenology

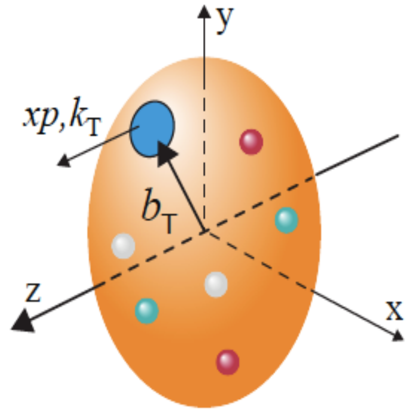
RHIC is the excellent and unique facility to test this (W/Z – DY)!

"Big" questions to be answered, …

❑ How to probe the spatial distribution of quarks and gluons?

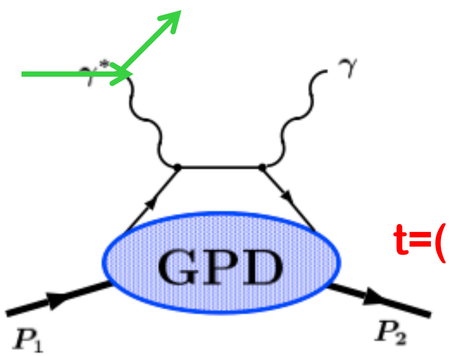
Need observables with two different momentum scales:

$$Q_1 \gg Q_2 \sim 1/R \sim \Lambda_{\rm QCD}$$



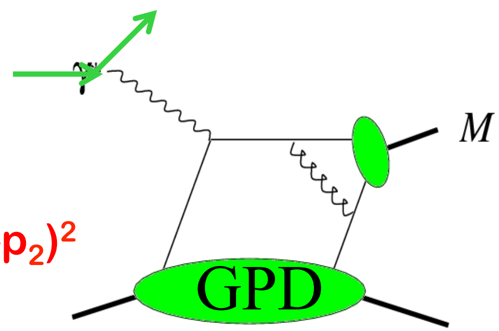
- ✧ **Hard scale:** Q_1 **localizes the probe to see the particle nature of quarks/gluons**
- ✧ **"Soft" scale:** Q_2 **could be more sensitive to the information at "fermi" scale**

❑ Two-scale observables with the hadron unbroken:

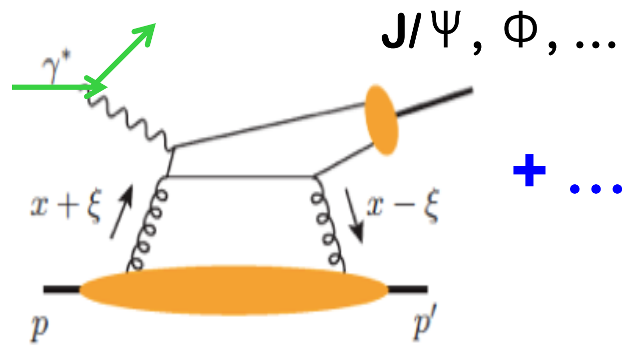


+

t=$(p_1-p_2)^2$



+



+ …

DVCS: $Q^2 \gg |t|$　　**DVEM: $Q^2 \gg |t|$**　　**EHMP: $Q^2 \gg |t|$**

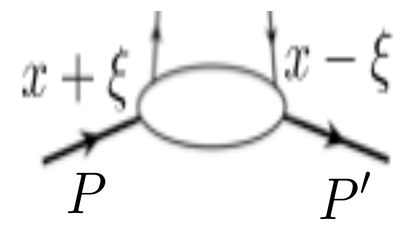
- ✧ **Observables with TWO very different scales –** ***QCD collinear factorization***
- ✧ **GPDs: Fourier Transform of t-dependence gives spatial b_T-dependence**

"Big" questions to be answered, …

❑ Definition of GPDs - Quark "form factor":

See also Weiss's talk

$$
\begin{aligned}
F_q(x,\xi,t,\mu^2) &= \int \frac{d\lambda}{2\pi} \mathrm{e}^{-ix\lambda} \langle P' | \bar{\psi}_q(\lambda/2) \frac{\gamma\cdot n}{2P\cdot n} \psi_q(-\lambda/2) | P \rangle \\
&\equiv H_q(x,\xi,t,\mu^2) \left[\bar{\mathcal{U}}(P')\gamma^\mu \mathcal{U}(P) \right] \frac{n_\mu}{2P\cdot n} \\
&+ E_q(x,\xi,t,\mu^2) \left[\bar{\mathcal{U}}(P') \frac{i\sigma^{\mu\nu}(P'-P)_\nu}{2M} \mathcal{U}(P) \right] \frac{n_\mu}{2P\cdot n}
\end{aligned}
$$



with $\xi = (P'-P)\cdot n/2 \;\; \text{and} \;\; t = (P'-P)^2 \;\Rightarrow\; -\Delta_\perp^2 \;\; \text{if} \;\; \xi \to 0$

$\tilde{H}_q(x,\xi,t,Q), \quad \tilde{E}_q(x,\xi,t,Q)$ **Different quark spin projection**

Effectively, QCD collinear factorization to connect GPDs to x-sections!

❑ its role in solving the spin puzzle:

Ji, PRL78, 1997

$$
\begin{aligned}
J_q &= \frac{1}{2} \lim_{t\to 0} \int dx\, x \left[H_q(x,\xi,t) + E_q(x,\xi,t) \right] \\
&= \frac{1}{2}\Delta q + L_q
\end{aligned}
$$

Quark's orbital contribution to proton's spin?

❑ Connection to normal quark distribution:

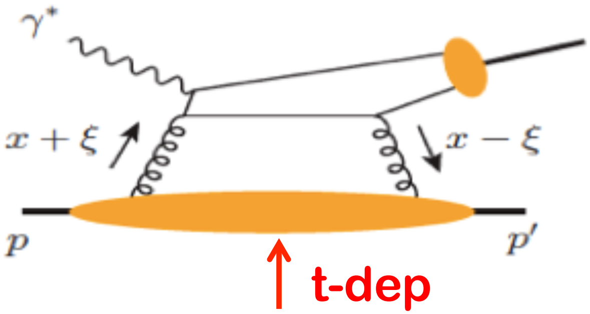
$H_q(x,0,0,\mu^2) = q(x,\mu^2)$ **The limit when** $\xi \to 0$

Exclusive DIS, Spatial imaging, …

❑ Exclusive vector meson production:

$$\frac{d\sigma}{dx_B dQ^2 dt}$$

EIC-WhitePaper



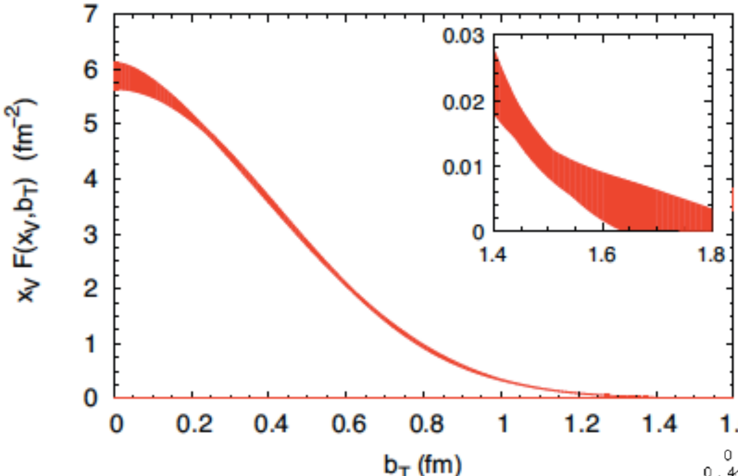
J/Ψ, Φ, …

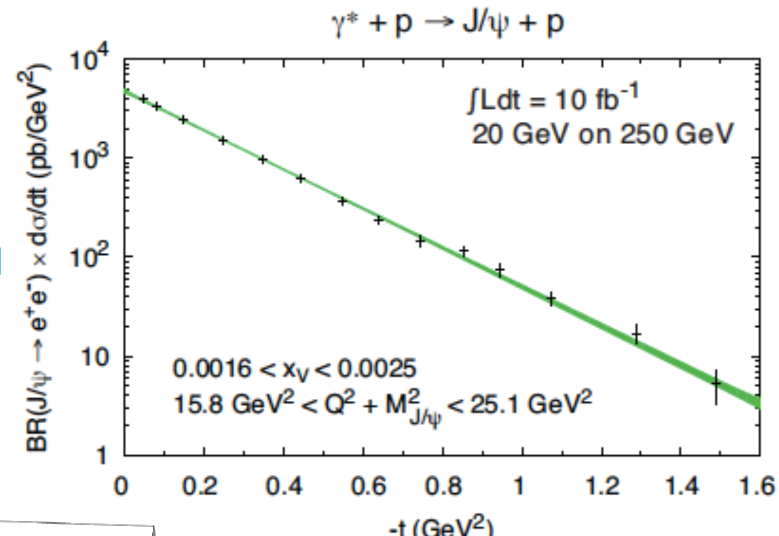
✧ Fourier transform of the t-dep

Spatial imaging of glue density

✧ Resolution ~ 1/Q or $1/M_Q$

❑ Gluon imaging from simulation:

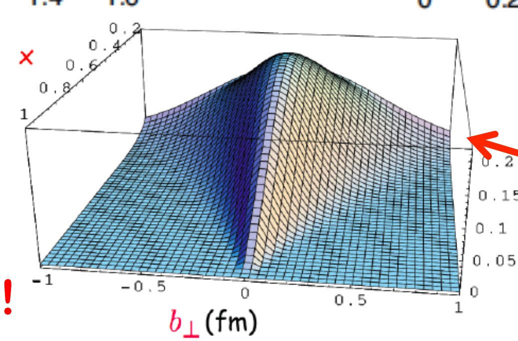




Only possible at the EIC

"Proton" radius?

Radius of gluon density (x)!

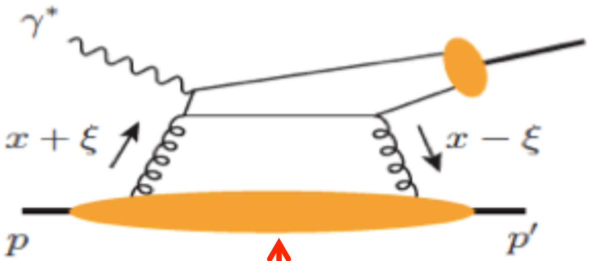


How spread at small-x?
Color confinement

"Big" questions to be answered, …

- Exclusive vector meson production:

$$\frac{d\sigma}{dx_B dQ^2 dt}$$ EIC-WhitePaper



J/Ψ, Φ, …

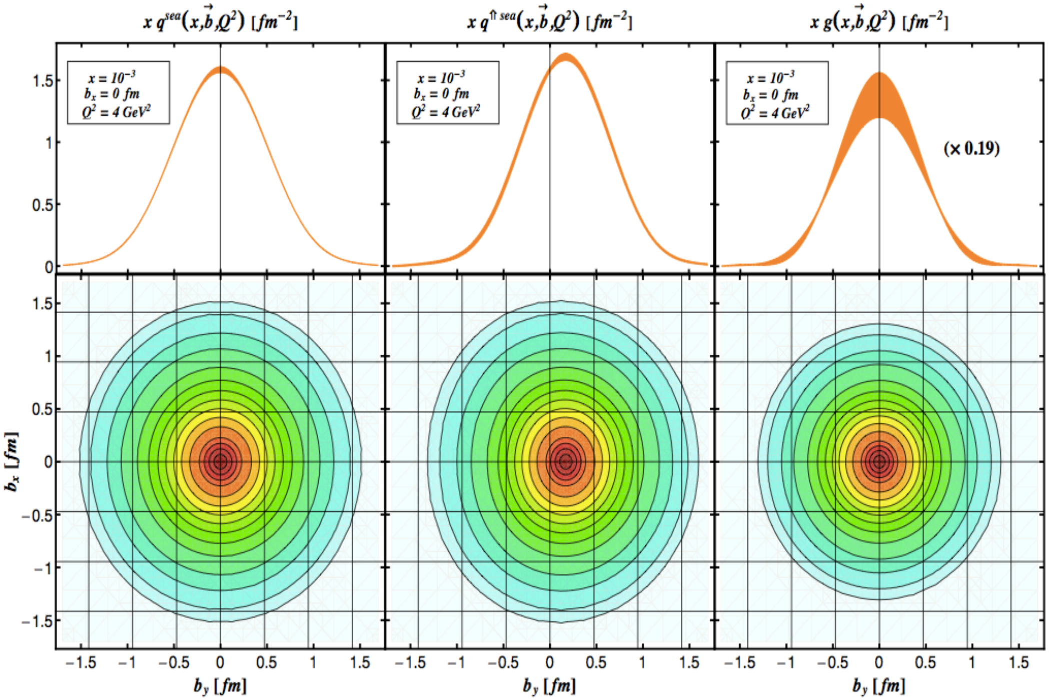
↑ t-dep

✧ Fourier transform of the t-dep

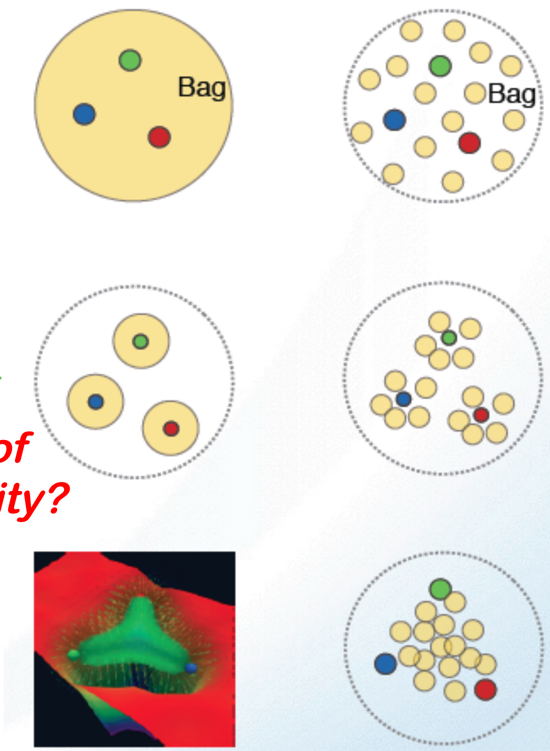
➡ *Spatial imaging of glue density*

✧ Resolution ~ 1/Q or 1/M_Q

- Imaging – "radius" of parton density:



EIC simulation



"radius" of gluon density?

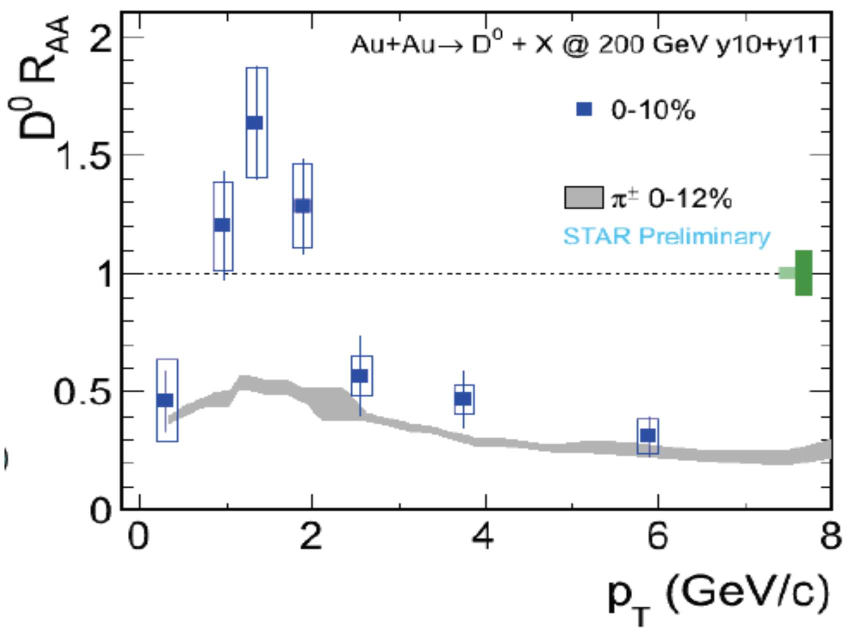
Emergence of hadrons/Jets – A puzzle

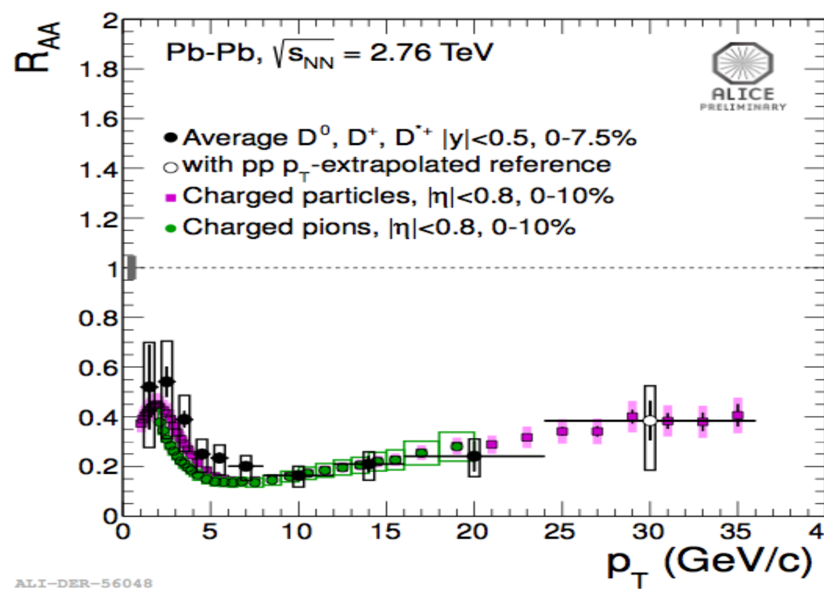
See also Vitev's talk

- ❑ **Emergence of hadrons:**

  How do hadrons emerge from a created quark or gluon?
  How is the color of quark or gluon neutralized?

- ❑ **Strong suppression of heavy flavors in AA collisions:**

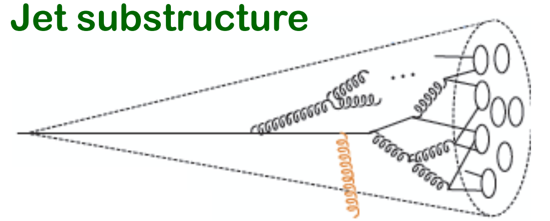




- ❑ **Need a femtometer detector or "scope":**

  Nucleus, a laboratory for QCD
  A "vertex" detector: Evolution of hadronization

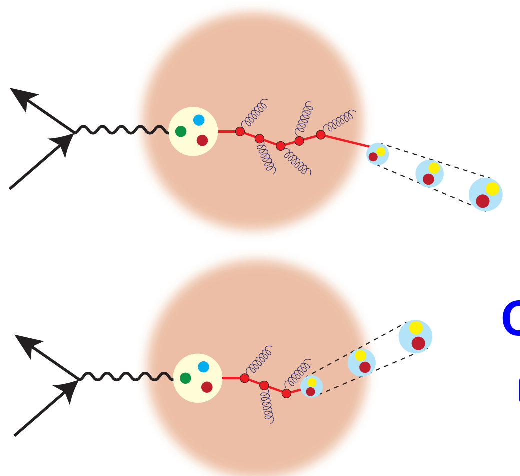
Jet substructure



Boosted hadronization

"Big" questions to be answered, ...

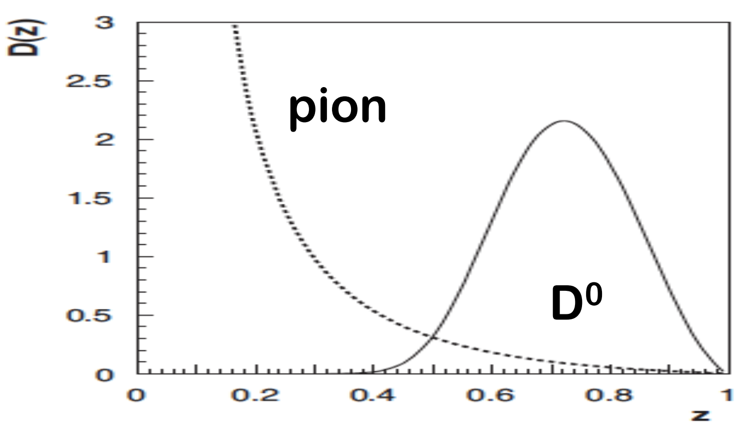
- **Emergence of a hadron?**

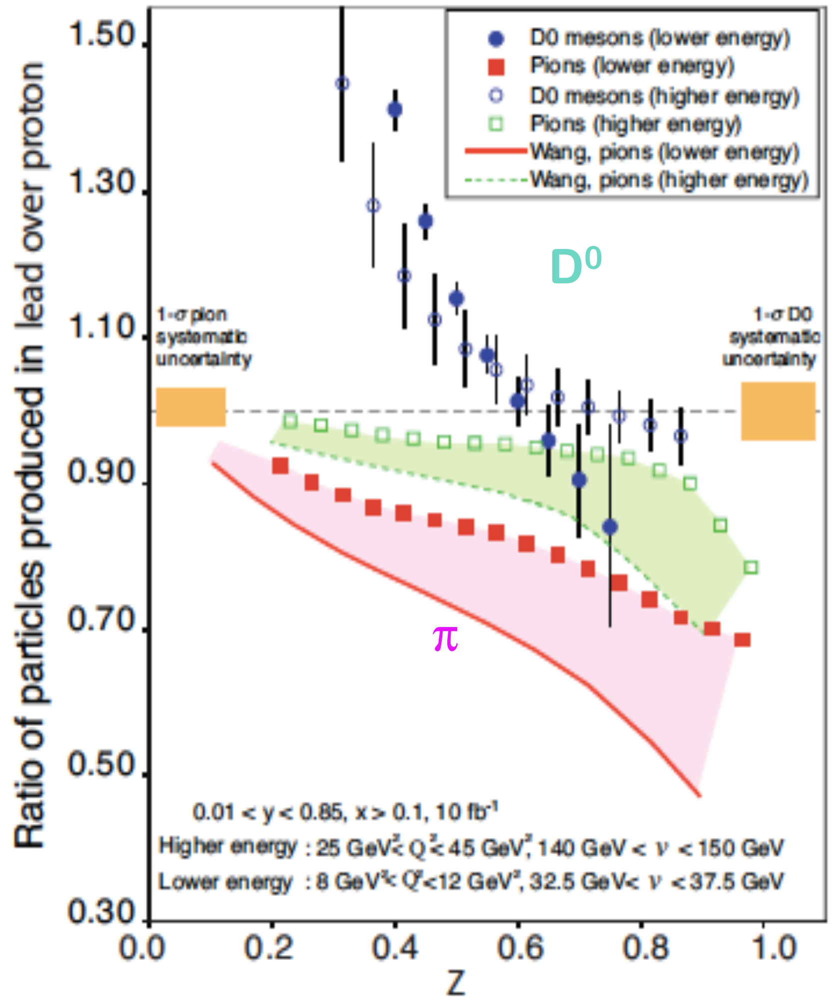


$$\nu = \frac{Q^2}{2mx}$$

Control of ν and medium length!

- **Heavy quark energy loss:**
  - **Mass dependence of fragmentation**



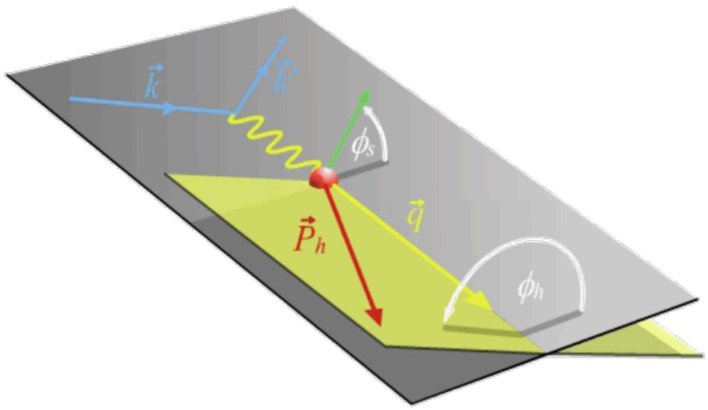


Need the collider energy of EIC and its control on parton kinematics

Color fluctuation – azimuthal asymmetry at EIC

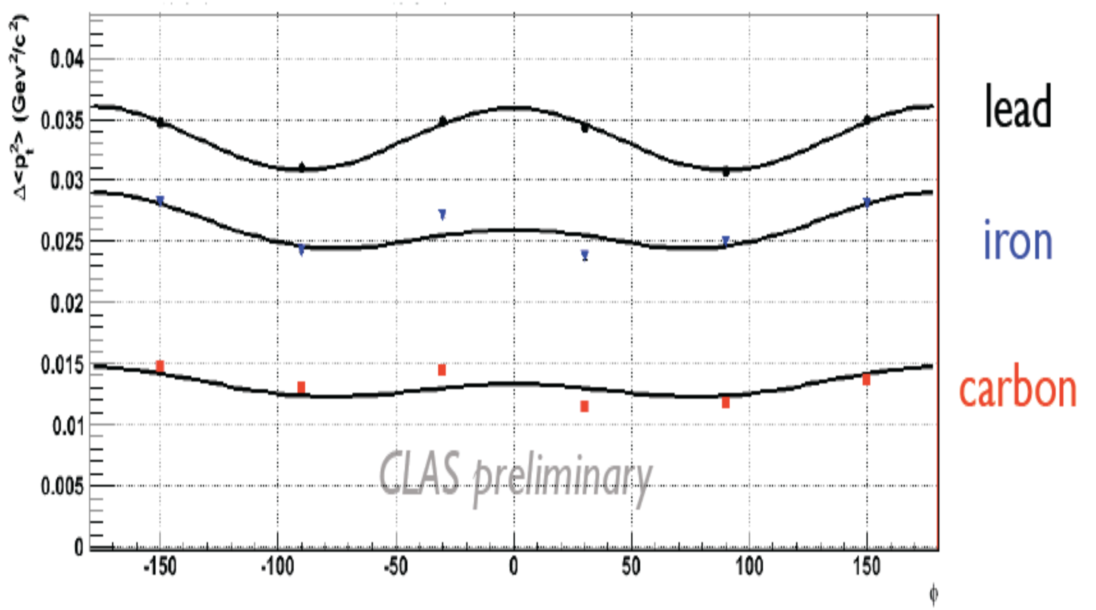
Hicks, KEK-JPAC2013

- Preliminary low energy data:



$$\langle p_T^2(\phi_{pq})\rangle_A = \int dp_T^2\, p_T^2 \frac{d\sigma_{eA}}{dx_B dQ^2 dp_T^2 d\phi} \Big/ \frac{d\sigma_{eA}}{dx_B dQ^2}$$

$$\langle \Delta p_T^2(\phi)\rangle_{AN} \equiv \langle p_T^2(\phi)\rangle_A - \langle p_T^2(\phi)\rangle_N$$



Contain terms in cos(ϕ_{pq}) and cos($2\phi_{pq}$)
only statistical uncertainties shown

- Classical expectation:

Any distribution seen in Carbon should be washed out in heavier nuclei

- Surprise:

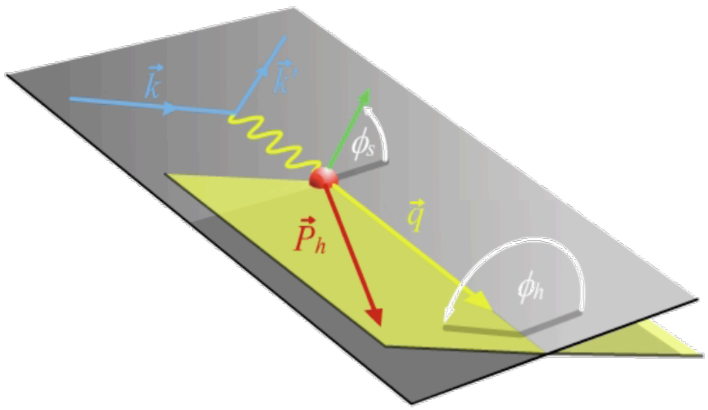
Azimuthal asymmetry in transverse momentum broadening

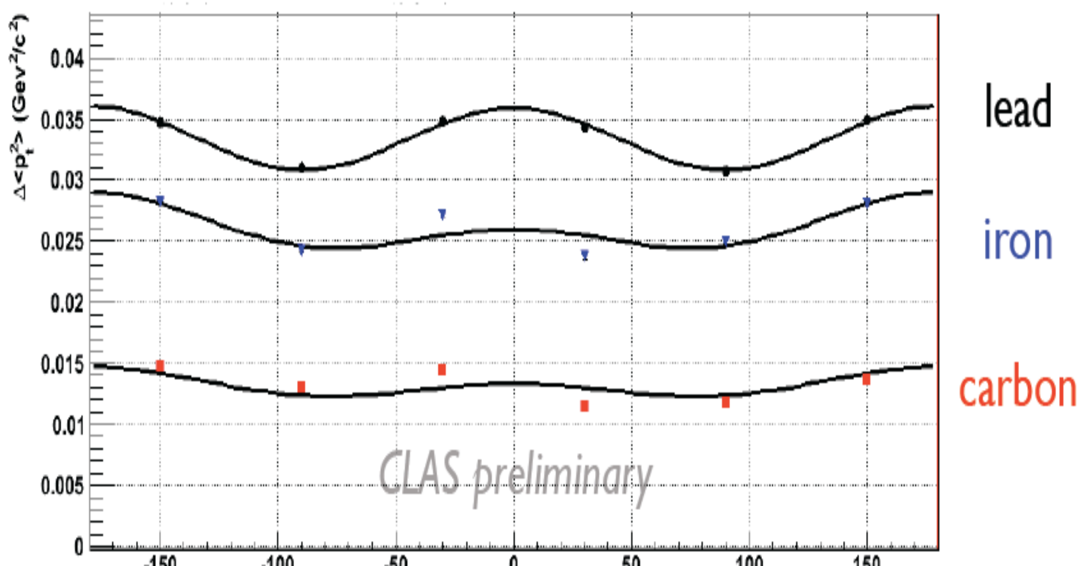
➡ *Fluctuation and v_n at EIC!*

Color fluctuation – azimuthal asymmetry at EIC

Hicks, KEK-JPAC2013

- ❑ Preliminary low energy data:





$$\langle p_T^2(\phi_{pq})\rangle_A = \int dp_T^2\, p_T^2 \frac{d\sigma_{eA}}{dx_B dQ^2 dp_T^2 d\phi} \Big/ \frac{d\sigma_{eA}}{dx_B dQ^2}$$

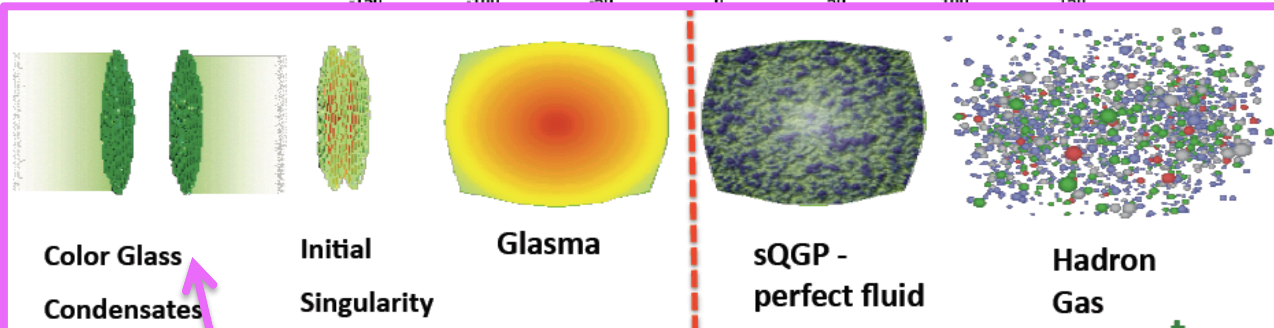
$$\langle \Delta p_T^2(\phi)\rangle_{AN} \equiv \langle p_T^2(\phi)\rangle_A - \langle$$

- ❑ Classical expecta

  Any distribution se

- ❑ Surprise:

  Azimuthal asymmet



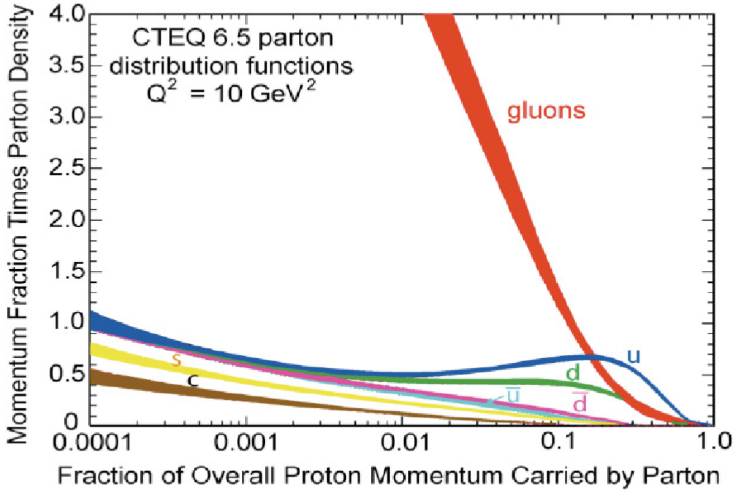
Provide important information for the initial conditions in Nucleus-Nucleus Collisions

➡ *Fluctuation and v_n at EIC!*

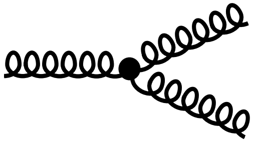
"Big" questions to be answered, …

See also Stasto's talk

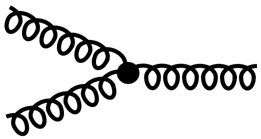
- ❑ Run away gluon density at small x?



What causes the low-x rise?
gluon radiation
– non-linear gluon interaction



What tames the low-x rise?
gluon recombination
– non-linear gluon interaction



- ❑ QCD vs. QED:

QCD – gluon in a proton:

$$Q^2 \frac{d}{dQ^2} xG(x,Q^2) \approx \frac{\alpha_s N_c}{\pi} \int_x^1 \frac{dx'}{x'} x' G(x',Q^2)$$

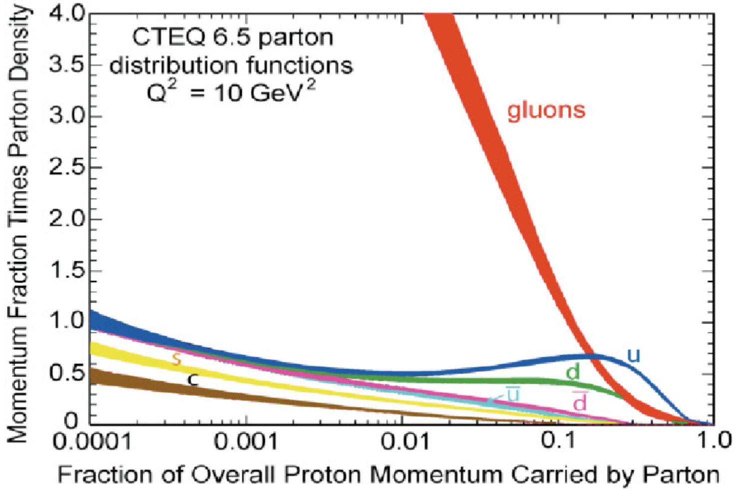
QED – photon in a positronium:

$$Q^2 \frac{d}{dQ^2} x\phi_\gamma(x,Q^2) \approx \frac{\alpha_{em}}{\pi} \left[-\frac{2}{3} x\phi_\gamma(x,Q^2) + \int_x^1 \frac{dx'}{x'} x' [\phi_{e^+}(x',Q^2) + \phi_{e^-}(x',Q^2)] \right]$$

- ✧ At very small-x, proton is "black", positronium is still transparent!
- ✧ Recombination of large numbers of glue could lead to saturation phenomena

"Big" questions to be answered, …

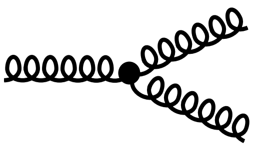
❑ Run away gluon density at small x?



What causes the low-x rise?

gluon radiation

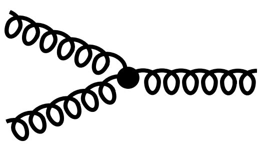
– non-linear gluon interaction



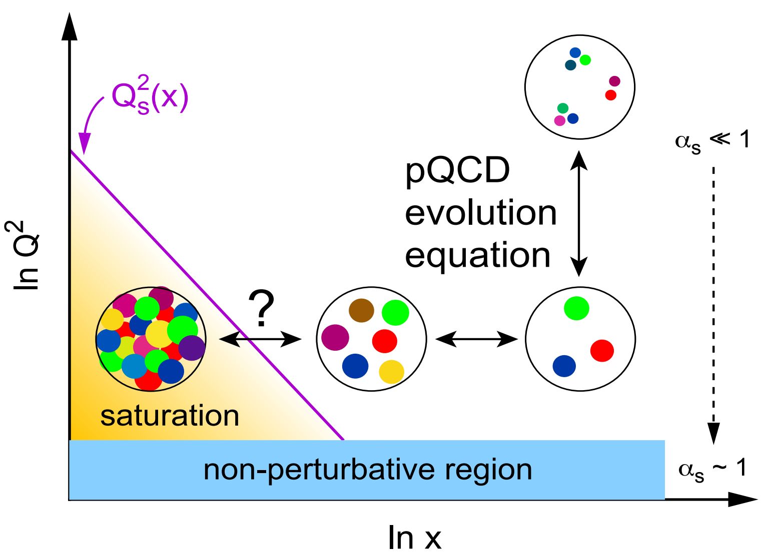
What tames the low-x rise?

gluon recombination

– non-linear gluon interaction

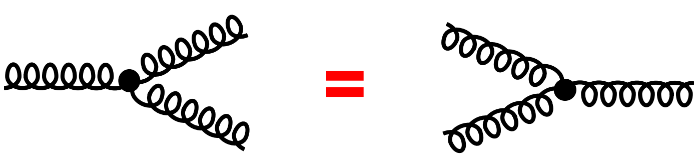


❑ Particle vs. wave feature:



Gluon saturation – Color Glass Condensate

Radiation = Recombination



at Q_s

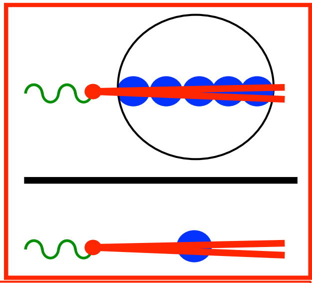
Leading to a collective gluonic system?

with a universal property of QCD?

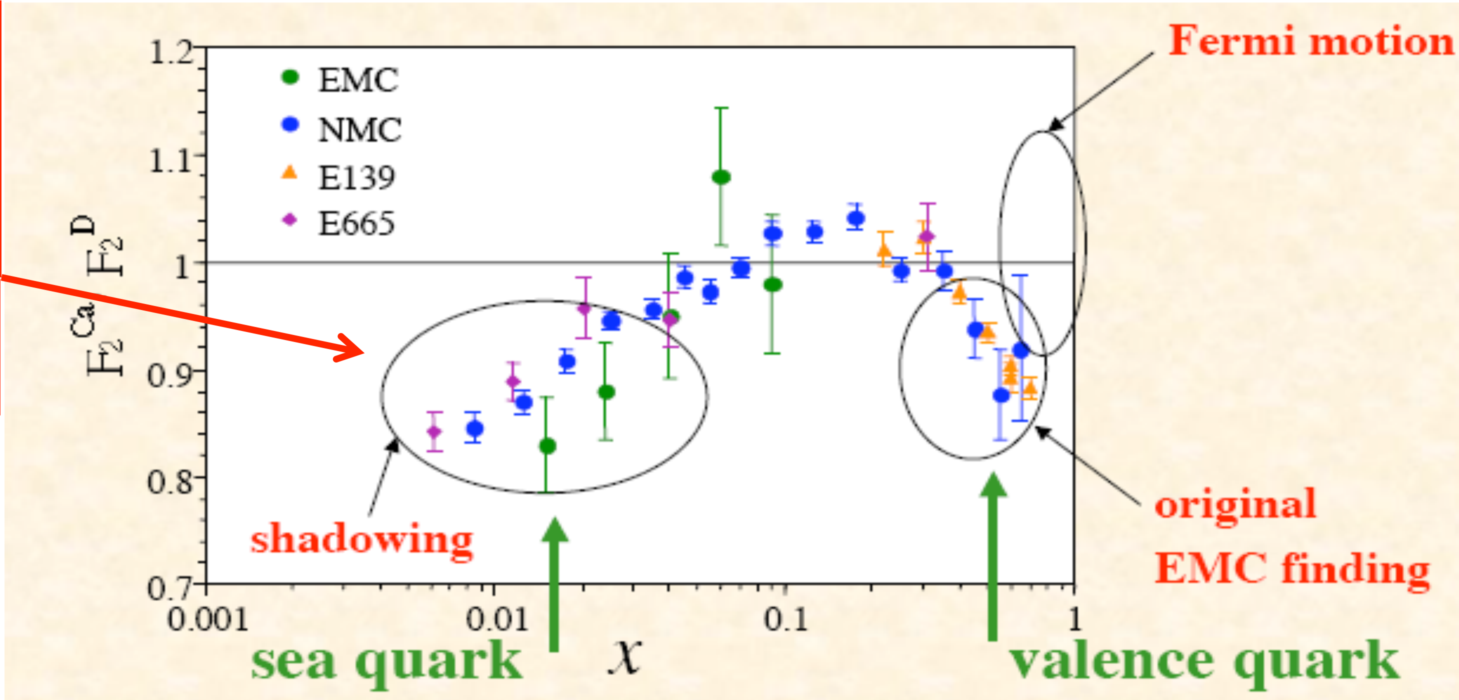
new effective theory QCD – CGC?

An “easiest” measurement at EIC

- ❑ Ratio of F_2: EMC effect, Shadowing and Saturation:



Color localized inside nucleons



An "easiest" measurement at EIC

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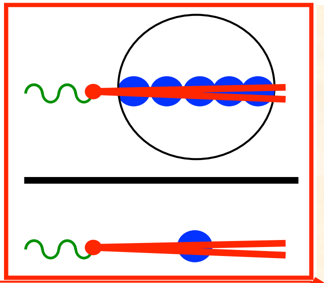
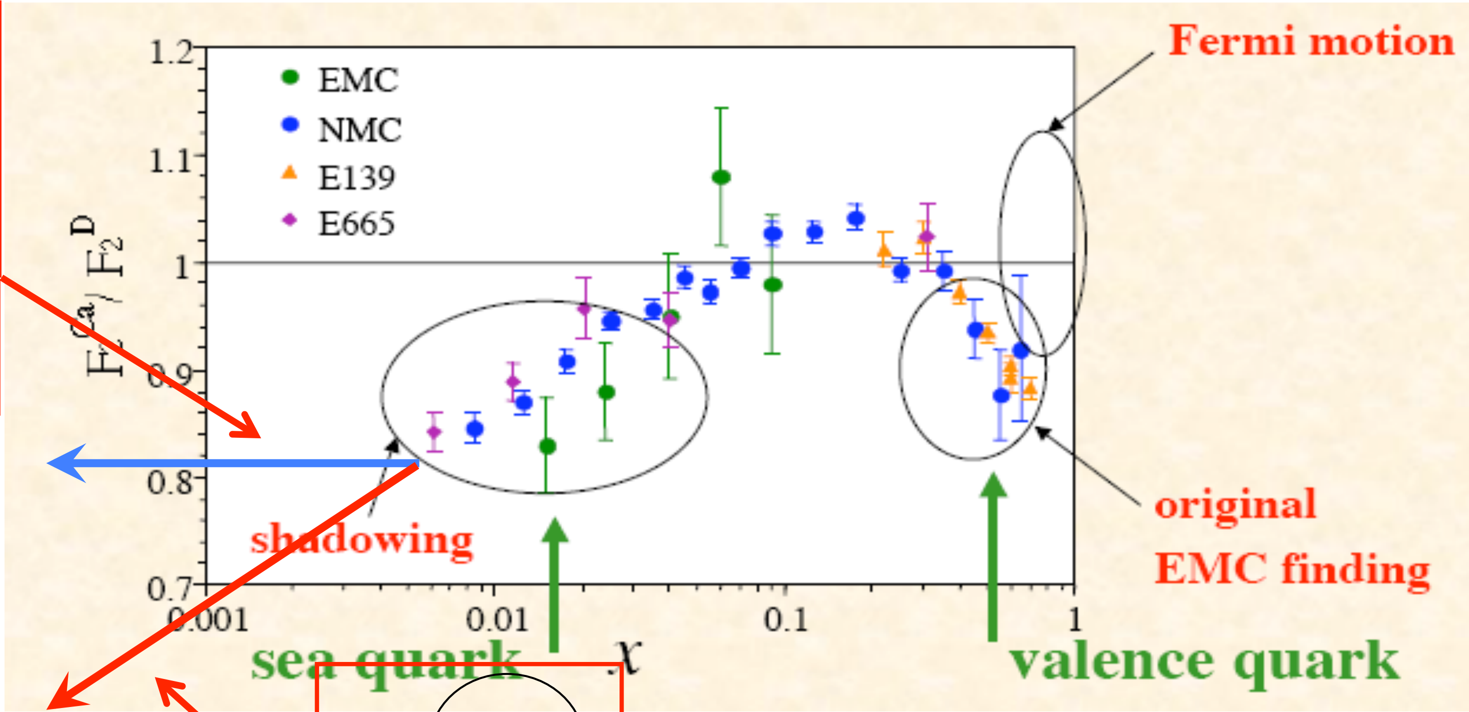
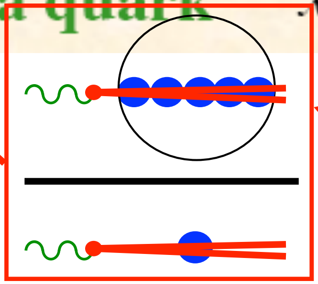


Color localized inside nucleons





Color leaks outside nucleons

- Questions:

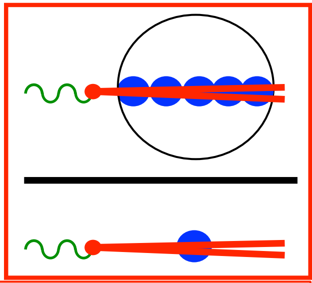
  Will the suppression/shadowing continue fall as x decreases?

  Could nucleus behaves as a large proton at small-x?

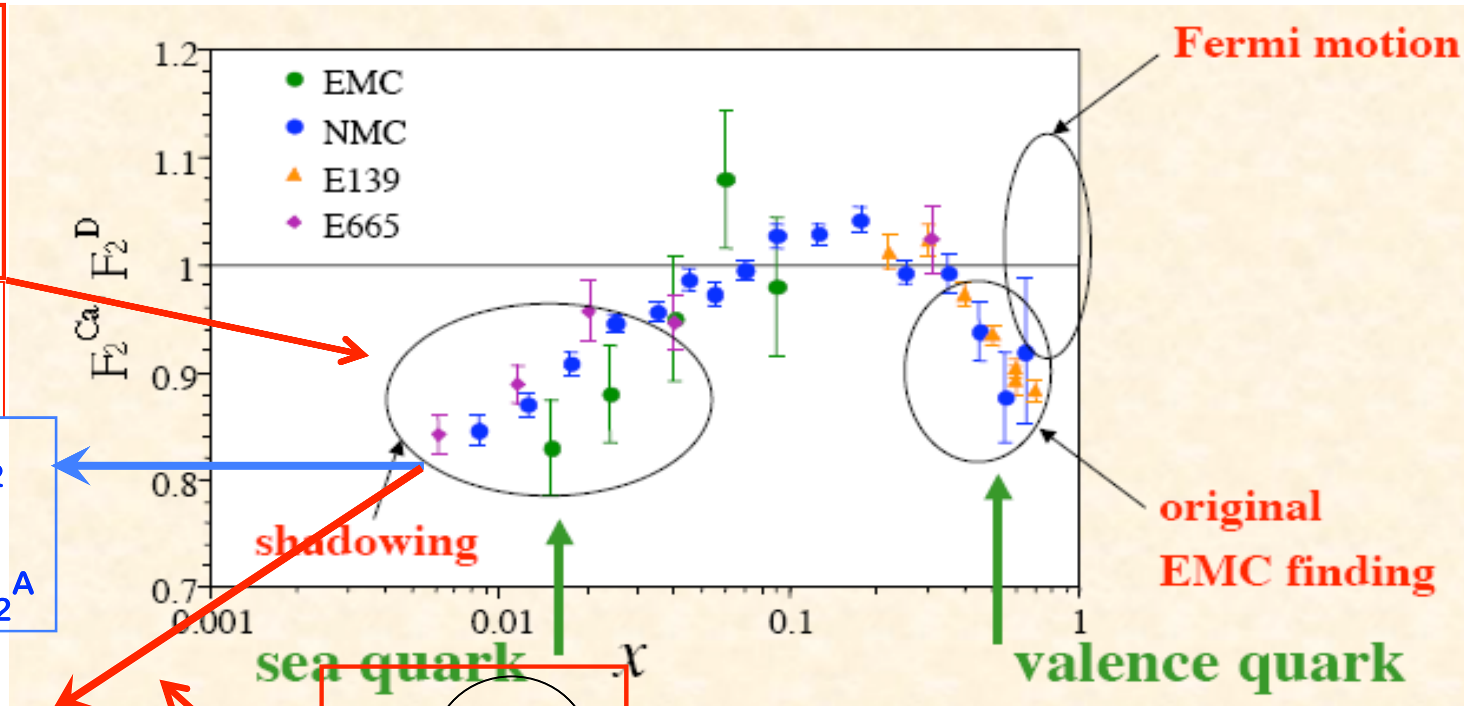
  Range of color correlation – could impact the center of neutron stars!

An “easiest” measurement at EIC

- **Ratio of F_2: EMC effect, Shadowing and Saturation:**



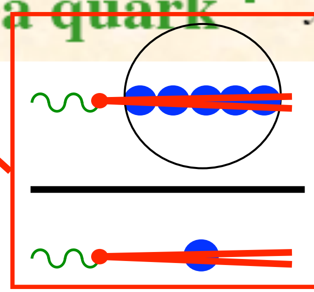
Color localized inside nucleons



Saturation in RF_2

=

No saturation in F_2^A



Color leaks outside nucleons

- **Questions:**

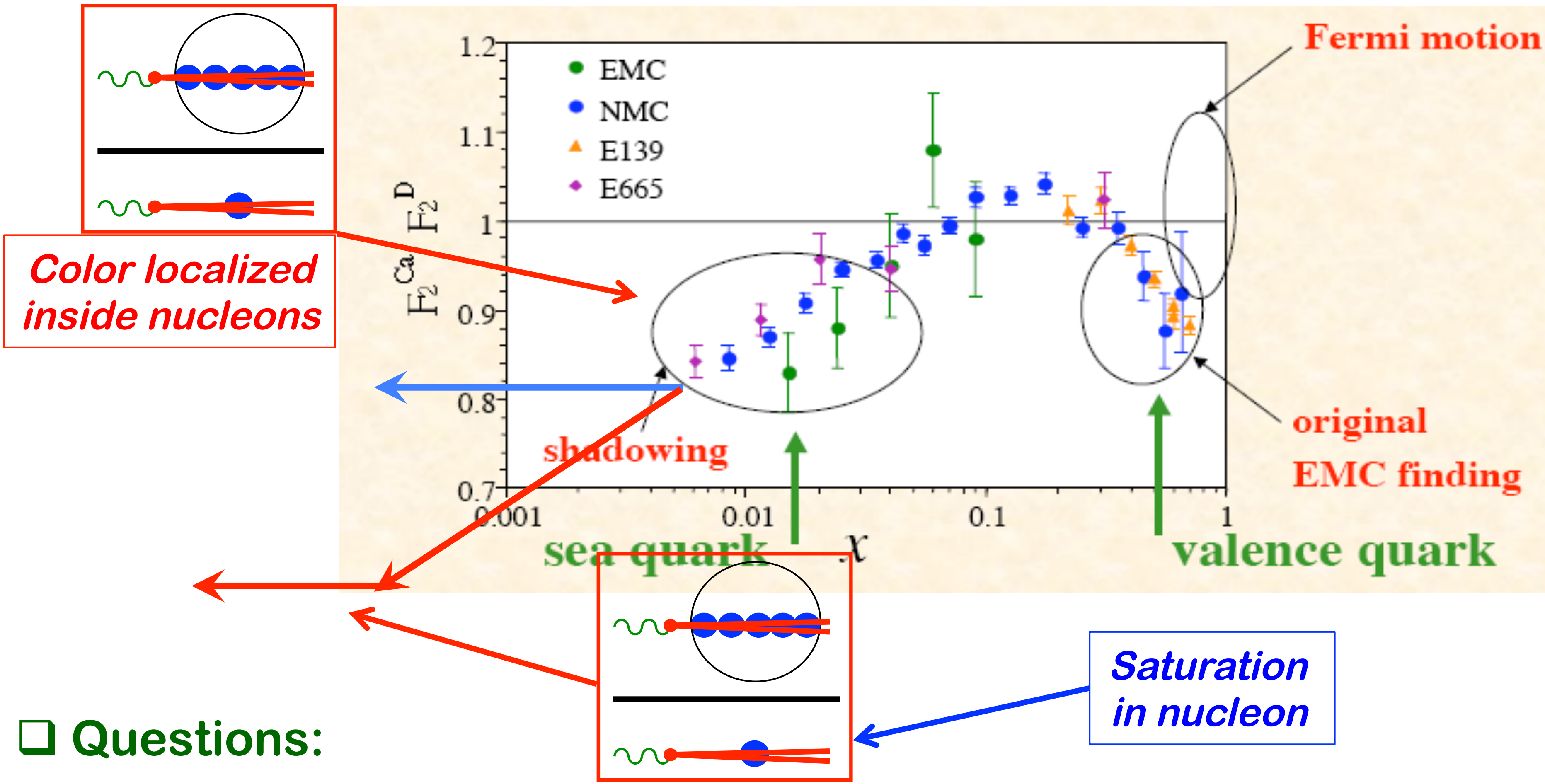
Will the suppression/shadowing continue fall as x decreases?

Could nucleus behaves as a large proton at small-x?

Range of color correlation – could impact the center of neutron stars!

An “easiest” measurement at EIC

- Ratio of F_2: EMC effect, Shadowing and Saturation:



- Questions:

  Will the suppression/shadowing continue fall as x decreases?

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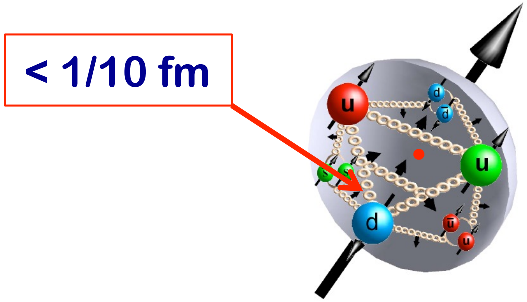
Summary



- QCD has been extremely successful in interpreting and predicting high energy experimental data, but, we still do not know much about hadron structure, and how hadrons are emerged from color charges

- Lattice QCD has made tremendous progresses, and expected to play a major role in determining hadron properties and structure

- With JLab12, RHIC, FNAL and facilities around the world, new data will challenge the theory, and new theory ideas will influence the experimental program

- But, EIC is a ultimate QCD machine, and absolutely needed:
  1) to discover and explore the quark/gluon structure and properties of hadrons and nuclei,
  2) to search for hints and clues of color confinement, and
  3) to measure the color fluctuation and color neutralization

Thanks!

Backup slides

Quantum Chromodynamics (QCD)

A beautiful and self-consistent QFT of quarks and gluons

- **Fields:**

$\psi_i^f(x)$ — **Quark fields:** spin-½ Dirac fermion (like electron)
Color triplet: $i = 1, 2, 3 = N_c$
Flavor: $f = u, d, s, c, b, t$

$A_{\mu,a}(x)$ — **Gluon fields:** spin-1 vector field (like photon)
Color octet: $a = 1, 2, ..., 8 = N_c^2 - 1$

- **QCD Lagrangian density:** … Bardeen, Fritzsch, Gell-Mann, Leutwyler, 1972,3

$$\mathcal{L}_{QCD}(\psi, A) = \sum_f \overline{\psi}_i^f \left[(i\partial_\mu \delta_{ij} - gA_{\mu,a}(t_a)_{ij})\gamma^\mu - m_f \delta_{ij} \right] \psi_j^f$$
$$-\frac{1}{4}\left[\partial_\mu A_{\nu,a} - \partial_\nu A_{\mu,a} - gC_{abc}A_{\mu,b}A_{\nu,c}\right]^2$$
$$+ \text{ gauge fixing} + \text{ghost terms}$$

- **QED Lagrangian density – force to hold atoms together:**

$$\mathcal{L}_{QED}(\phi, A) = \sum_f \overline{\psi}^f \left[(i\partial_\mu - eA_\mu)\gamma^\mu - m_f \right] \psi^f - \frac{1}{4}\left[\partial_\mu A_\nu - \partial_\nu A_\mu\right]^2$$

- ✧ QCD is much richer in dynamics than QED
- ✧ QCD is universally recognized as the correct theory of strong interactions
- ✧ But, No nucleons, No mesons, No nuclei, No XYZ, …

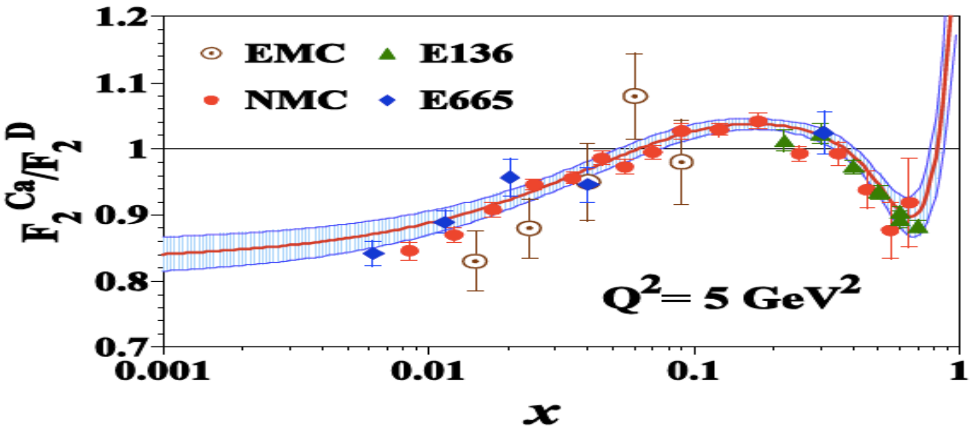
Nuclear landscape?

- **EMC discovery:**

  Nuclear landscape

  $\neq$ superposition

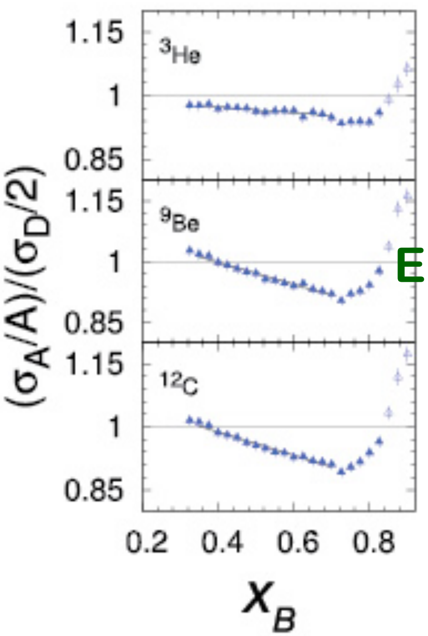
  of nucleon landscape

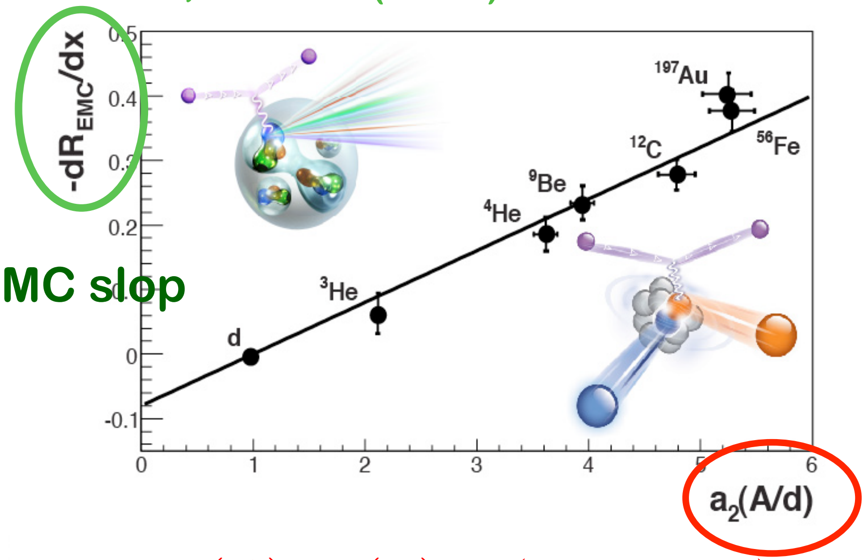


- **JLab12 measurement of EMC effect and beyond:**

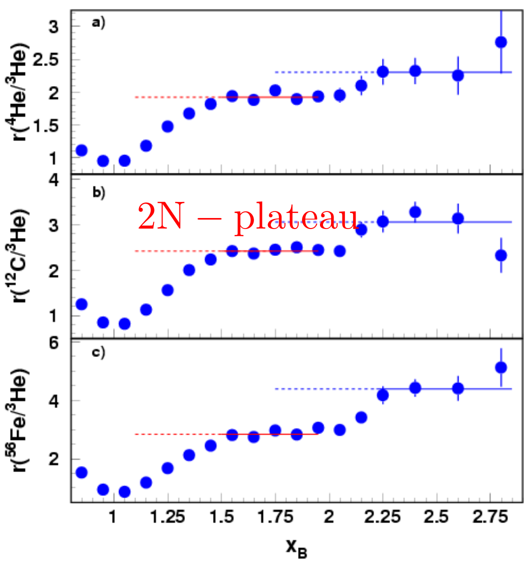
Weinstein et al., PRL 106, 052301 (2011)

SRC





EMC slop



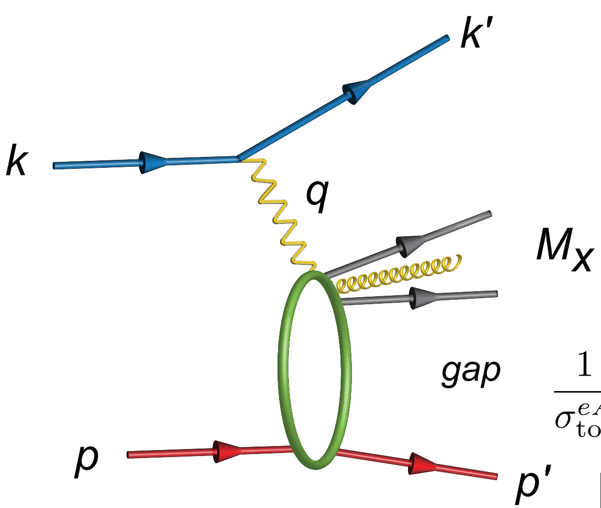
$$a_2\left(\frac{A}{D}\right) = \left(\frac{2}{A}\right)\frac{\sigma_A(2\mathrm{N}-\mathrm{plateau})}{\sigma_D(2\mathrm{N}-\mathrm{plateau})}$$

Cloet et al.

The best signature for gluon saturation

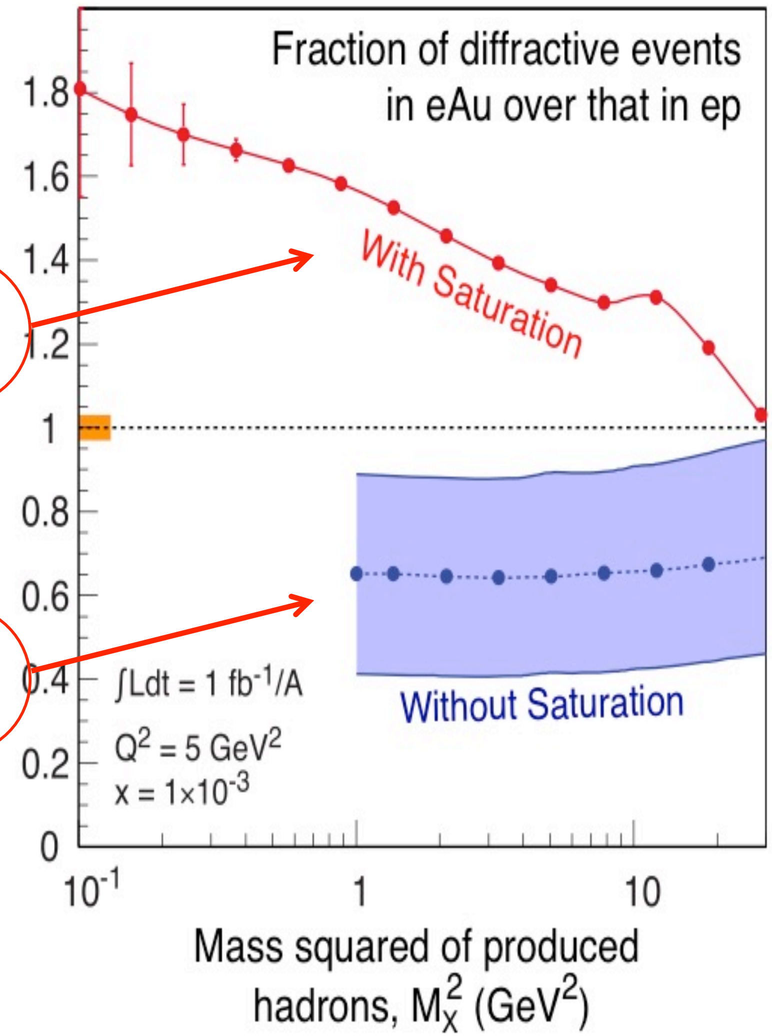
- Diffrative cross section:

$$\sigma_{\text{diff}} \propto [g(x, Q^2)]^2$$



$$\frac{1}{\sigma_{\text{tot}}^{eA}} \frac{d\sigma_{diff}^{eA}}{dM_x^2} \Big/ \frac{1}{\sigma_{\text{tot}}^{ep}} \frac{d\sigma_{diff}^{ep}}{dM_x^2} \sim \frac{25-30\%}{10-15\%} > 1$$

$$\frac{1}{\sigma_{\text{tot}}^{eA}} \frac{d\sigma_{diff}^{eA}}{dM_x^2} \Big/ \frac{1}{\sigma_{\text{tot}}^{ep}} \frac{d\sigma_{diff}^{ep}}{dM_x^2} \sim \left[\frac{g^p(x)}{g^A(x)}\right]_{\text{tot}} \left[\frac{g^A(x)}{g^p(x)}\right]_{\text{diff}}^2 < 1$$



At HERA

ep: 10-15% diffractive

At EIC eA, if Saturation/CGC

eA: 25-30% diffractive

Early work – E665 @ FNAL:

Nuclear shadowing, diffractive scattering and low momentumprotons in μ Xe interactions at 490 GeV Z. Phys. C 65, 225–244 (1995)